National Aeronautics and Space Administration

CELEBRATING 100 YEARS

NASA Langley Research Center 1917-2017

Propulsion Airframe Integration Testing Seminar

4/17/17

NASA LaRC Reid #3

A Storied Legacy, A Soaring Future

Agenda

National Aeronautics and Space Administration

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NASA Langley Research Center 1917-2017

Time*	Topic	Presenter
12:30 pm	Welcome - Introductions	Jeff Flamm
12:40 am	Why Do We Need Propulsion Testing? Thoughts on Bookkeeping (~40 Min)	Bob Berrier
1:20 pm	Aerodynamic Performance Testing (~1:20)	Fran Capone
2:40 pm	Break (10 min)	---
2:50 pm	Exhaust Simulation Methods (~40 MIN)	Bob Berrier
3:30 pm	Propulsion Tares - Where do they come from and how do you find them? (~45 Min)	Larry Leavitt
4:15 pm	Q&A	All
4:30 pm	Adjourn	---

16 Foot Transonic Wind Tunnel

National Aeronautics and Space Administration

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16 Foot Transonic Wind Tunnel

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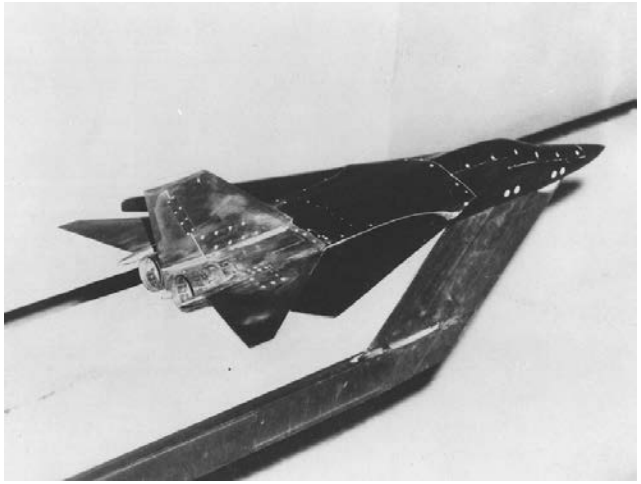
Douglas XA-26 Invader
November 1941

F-18 HARV June 1991

C-5M Super Galaxy
October 2001



F-111 Aardvark
April 1963

Boeing X-45B September 2002

https://crgis.ndc.nasa.gov/historic/16-Foot_Transonic_Tunnel#Photos_Ordered_by_Test_Log

16 Foot Transonic Wind Tunnel

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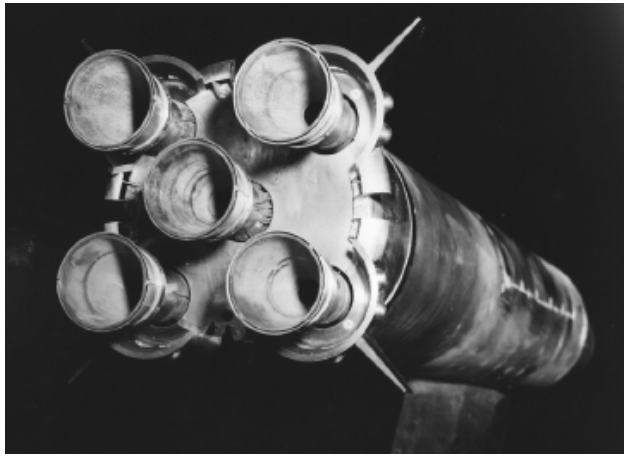
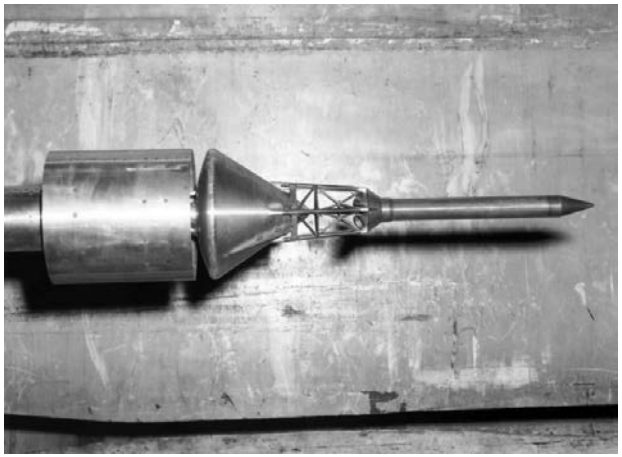
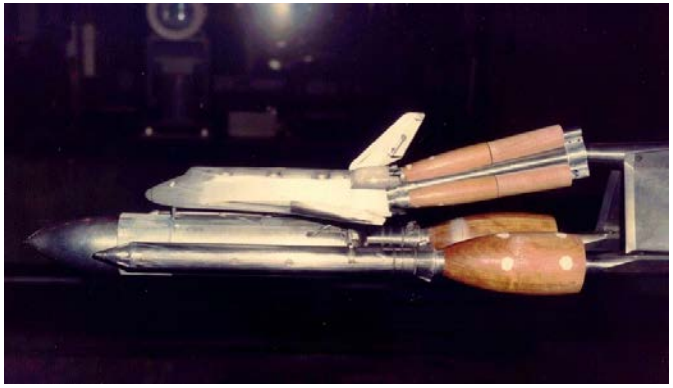


Saturn Launch Vehicle
December 1962



Apollo command/service module separation – Oct.1962



Space Shuttle
March 1976

https://crgis.ndc.nasa.gov/historic/16-Foot_Transonic_Tunnel#Photos_Ordered_by_Test_Log

Distinguished Speakers

National Aeronautics and Space Administration

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- Bob Berrier
- Fran Capone
- Larry Leavitt

Agenda

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CELEBRATING

100 YEARS

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WHY DO WE NEED PROPULSION TESTING*

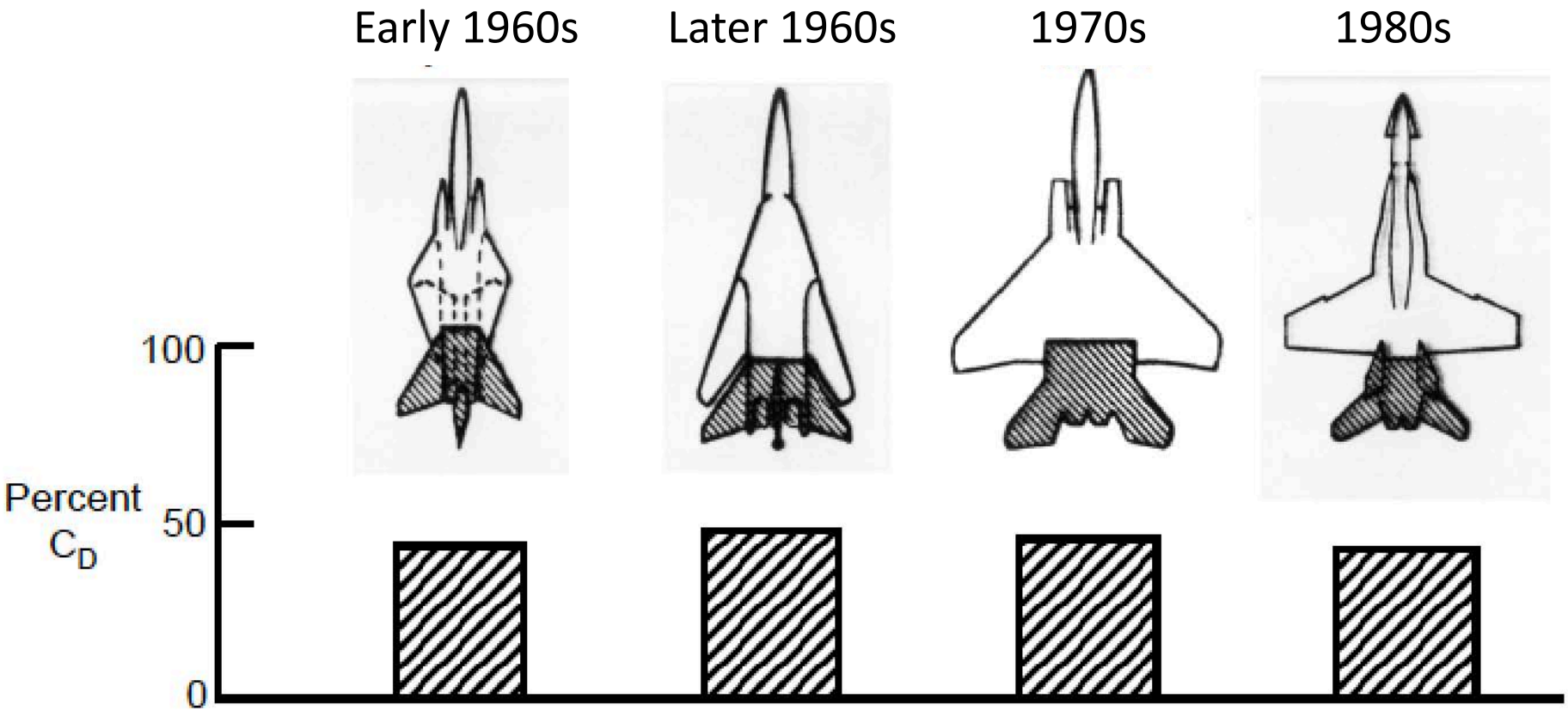
AND

BOOKKEEPING

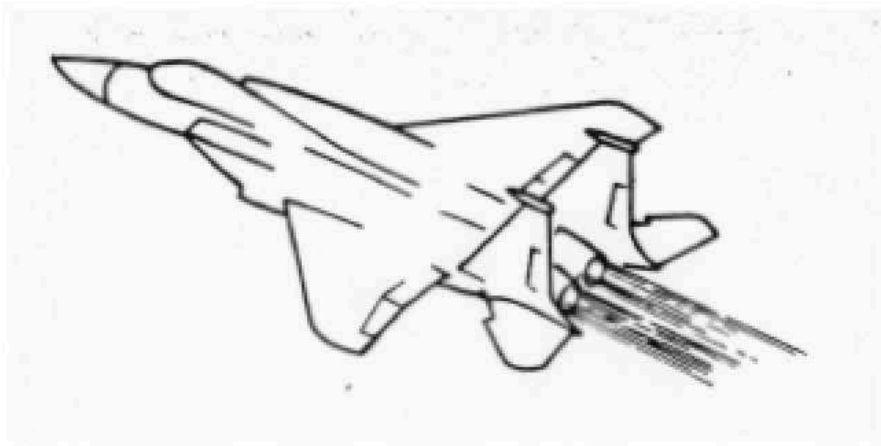
Presented by
Bob Berrier
4/17/17

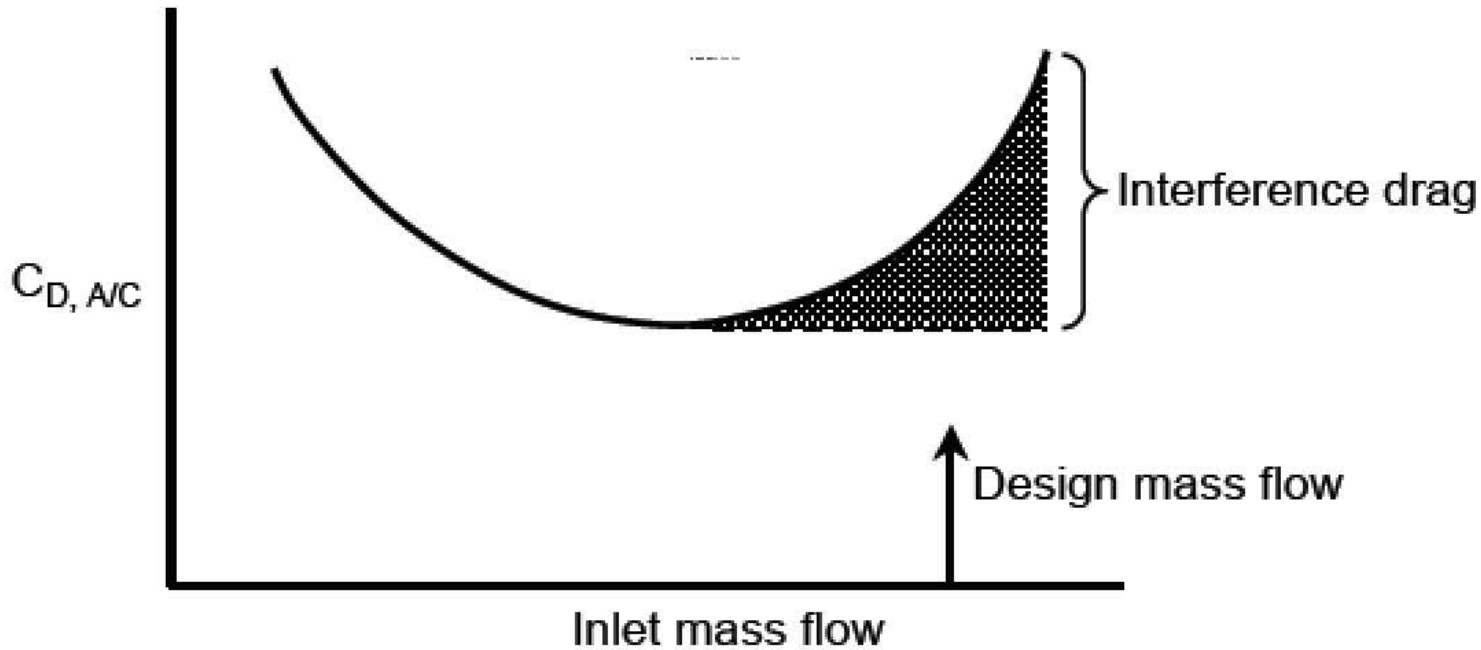
*** Care should be exercised as this nomenclature has been used for Inlet tests, nozzle tests, engine tests, and PAI tests**

AFT-END DRAG AT SUBSONIC SPEEDS



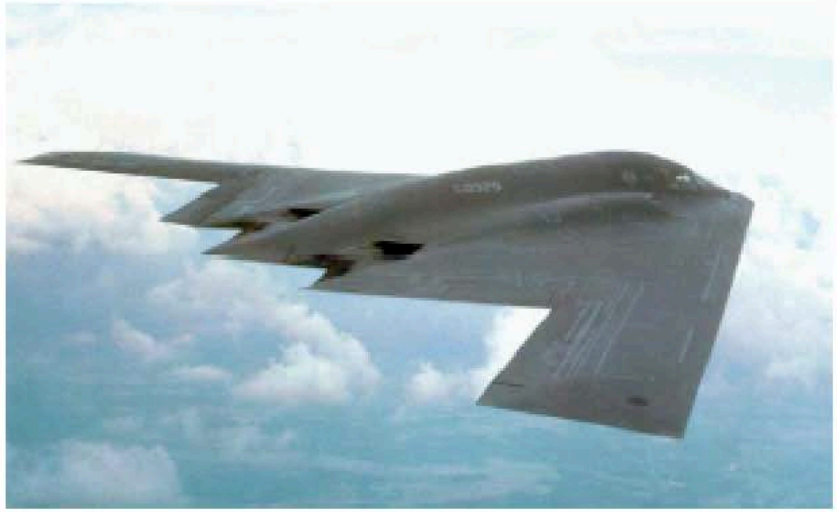
INLET/AIRFRAME INTERFERENCE EFFECTS

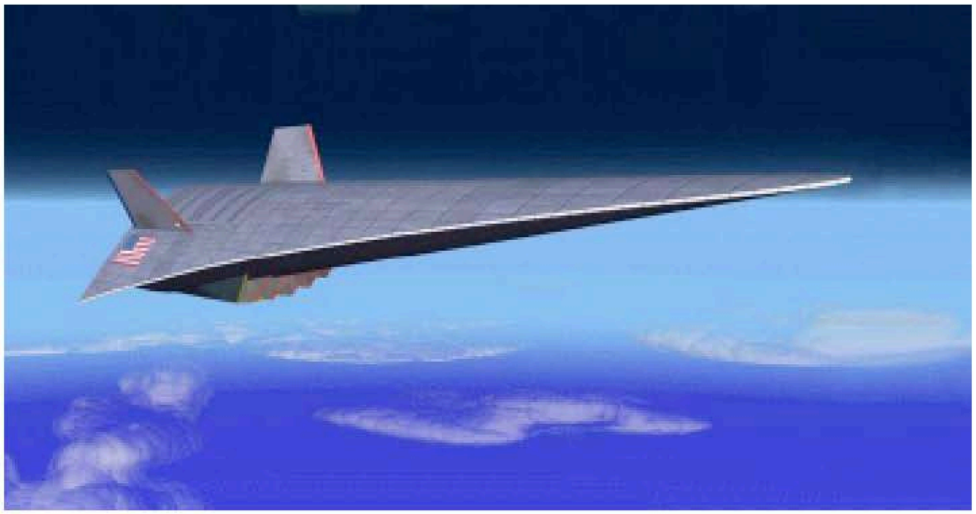




TYPICAL FIGHTER PROPULSION INSTALLATIONS

TYPICAL BOMBER PROPULSION INSTALLATIONS



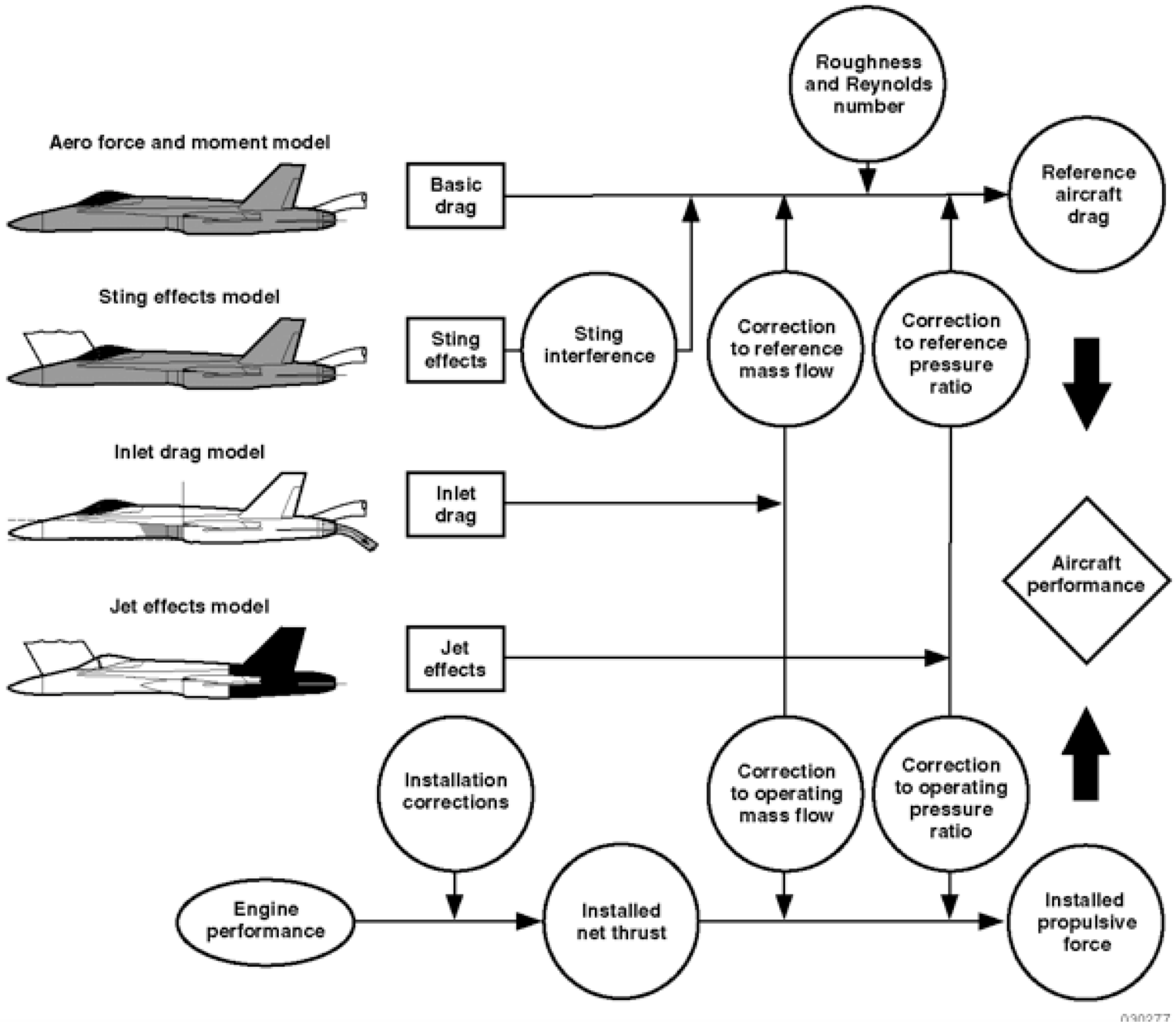


TYPICAL TRANSPORT PROPULSION INSTALLATIONS

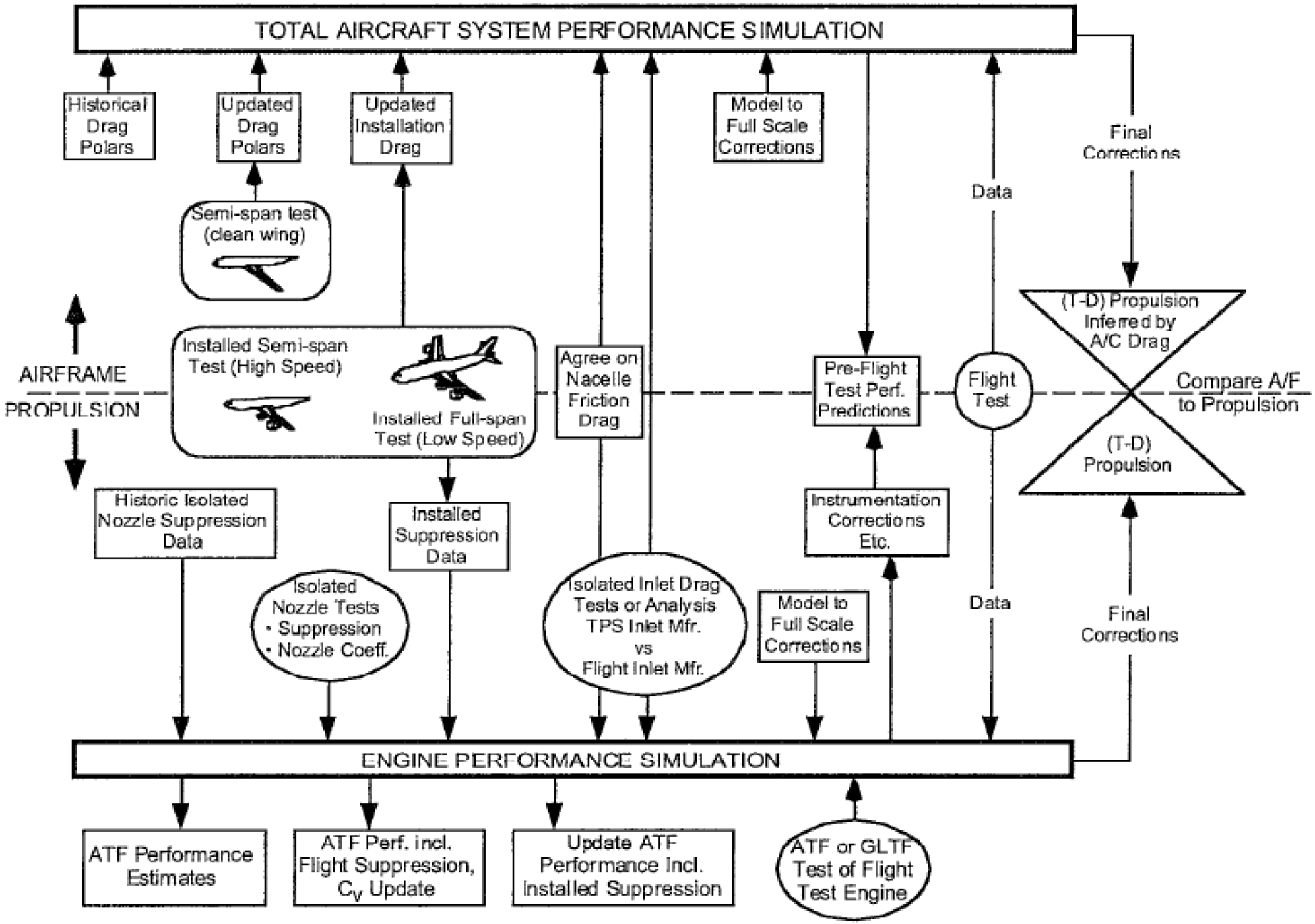
PROPULSION INTEGRATION TASKS

- Basic Research/Parametric Design Data
  - Nonaxisymmetric/Multifunction Nozzles
  - Tail interference
  - Theory/CFD validation
- Product Improvement
  - F-111, F-14, F-15, F-18, B-1B, B-2
- Evaluation of New Concepts
  - Distributed Propulsion
  - Blended Wing Concepts
  - Boundary Layer Ingestion
  - Low Boom Supersonic Config.
- Flight Performance Evaluation (Valid bookkeeping system that is agreed to by everyone is essential)
  - Corrections to Flight Aerodynamic and Engine Data Packages

TYPICAL BOOKKEEPING SYSTEM AND REQUIRED MODELS



SUCCESSFUL BOOKKEEPING RESULT – THRUST/DRAG CLOSURE



TYPICAL PROPULSION TESTS/MODELS/RESULTS

WHAT ARE THEY USED FOR?

PROPULSION COMPONENT TEST CONTRIBUTIONS

INLET SYSTEM

- Part of AC bookkeeping system
- Provides
  - Pressure recovery
  - Distortion
  - Operating geometry Δ
  - Spillage drag Δ

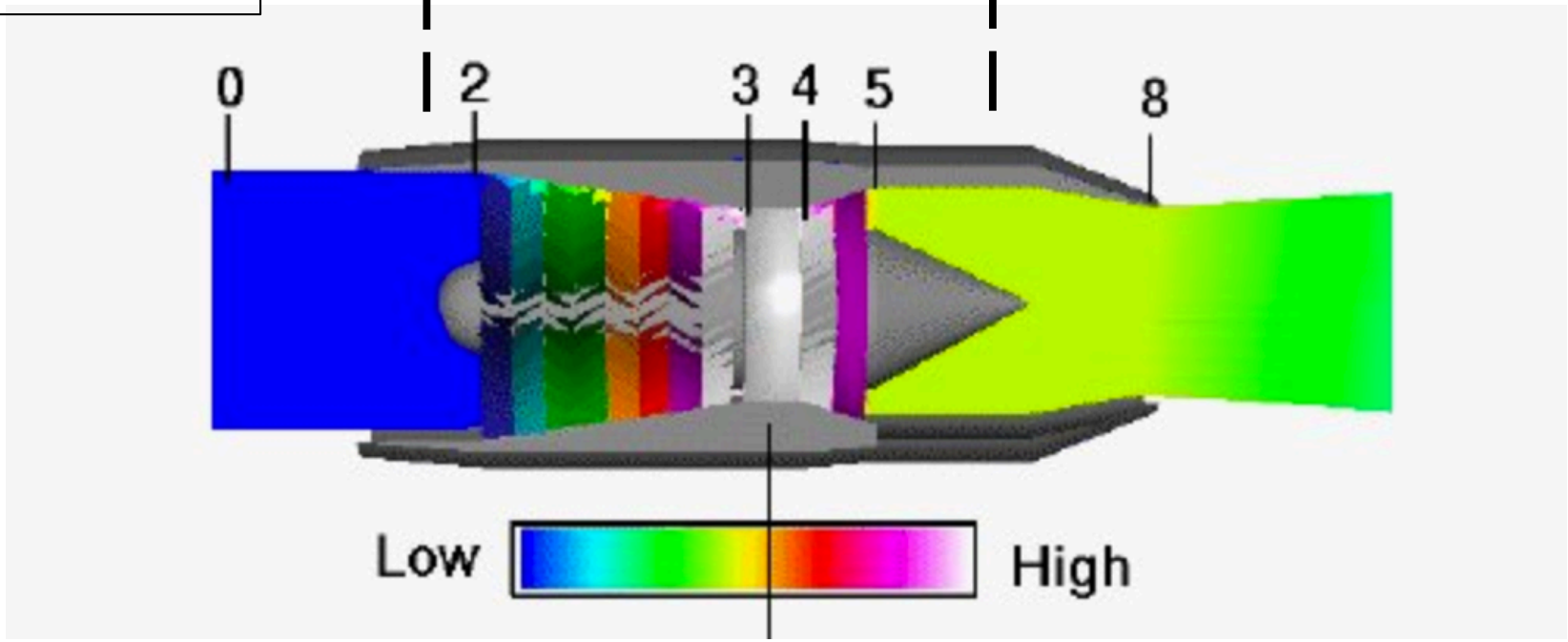
ENGINE

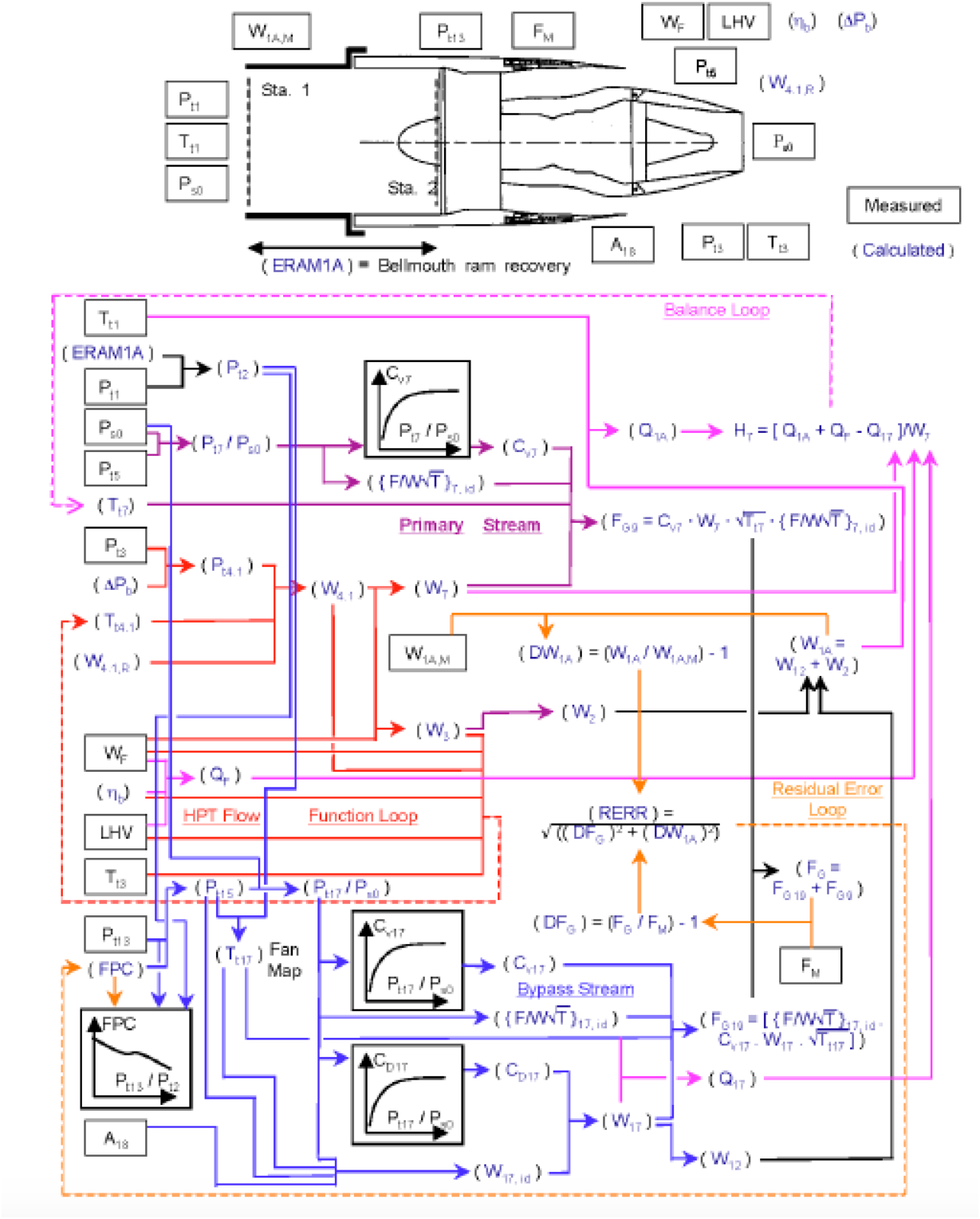
- Where full-scale thrust value comes from
- Separate bookkeeping system
- Uses info from inlet & exhaust tests and vice-versa

EXHAUST SYSTEM

- Part of AC bookkeeping system
- Does not provide full-scale thrust (not scalable)
- Provides
  - C_V (Nozzle efficiency)
  - C_D (Discharge coeff.)
  - Sting and Distortion Δ
  - Operating geometry Δ
  - Operating NPR Δ
  - Engine suppression

FOR AC PERF, ALL PARTIES **MUST** BE IN AGREEMENT



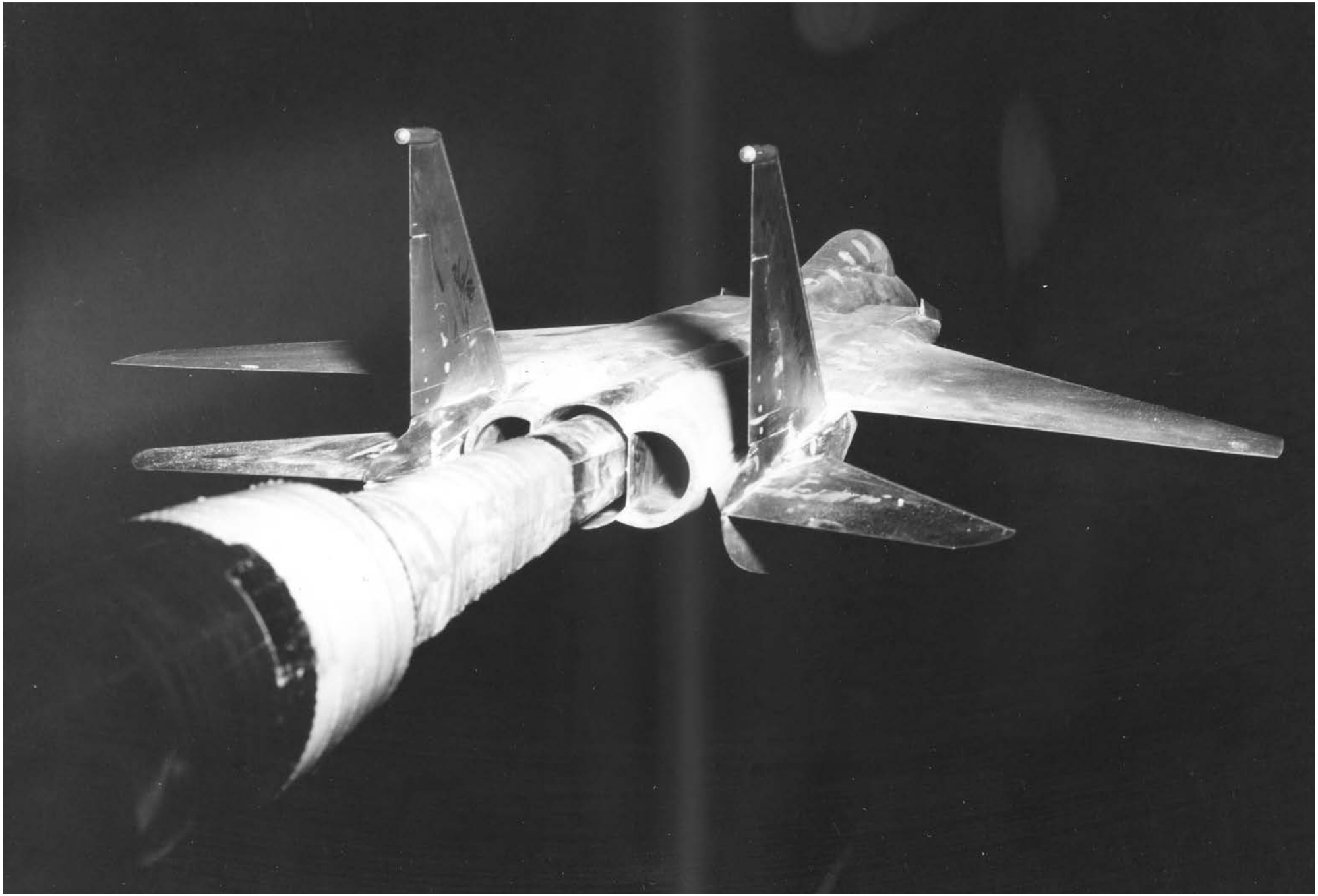


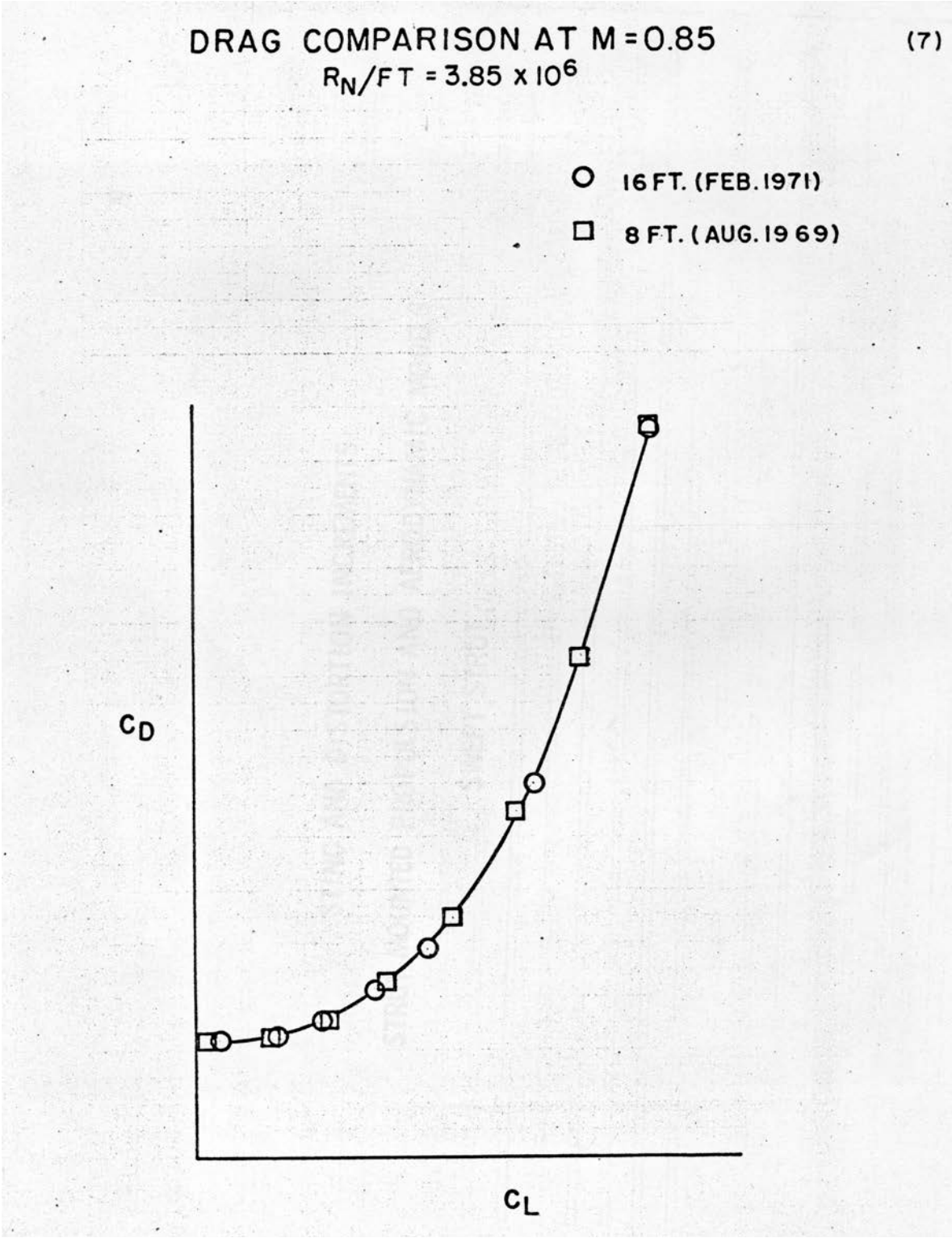
ENGINE MODEL

- TYPICAL ENGINE BOOKKEEPING SYSTEM - ONE OF MANY THRUST METHODS FROM SAE AIR 1703 AND SAE AIR 5450
- REQUIRES SOME INPUTS FROM GROUND TESTING
  - C_V
  - C_D
  - PRESSURE RECOVERY
  - DISTORTION
  - NOZZLE SUPPRESSION EFFECTS
  - SPILLAGE DRAG INCREMENTS
  - THROTTLE DEPENDENT INLET AND NOZZLE INCREMENTS

AERO MODEL

F-15 AERO MODEL





Drag Polar

- Fixed variables
  - Mach No.
  - Inlet Capture Ratio, A_0/A_C
  - NPR (Flow-Thru)
  - Roll/Sideslip Angles
  - Control Settings
  - Nozzle/Inlet Ext. Geometry
  - R_N
  - Weapon Load

TYPICAL DRAG POLOR CORRECTION ON F-111

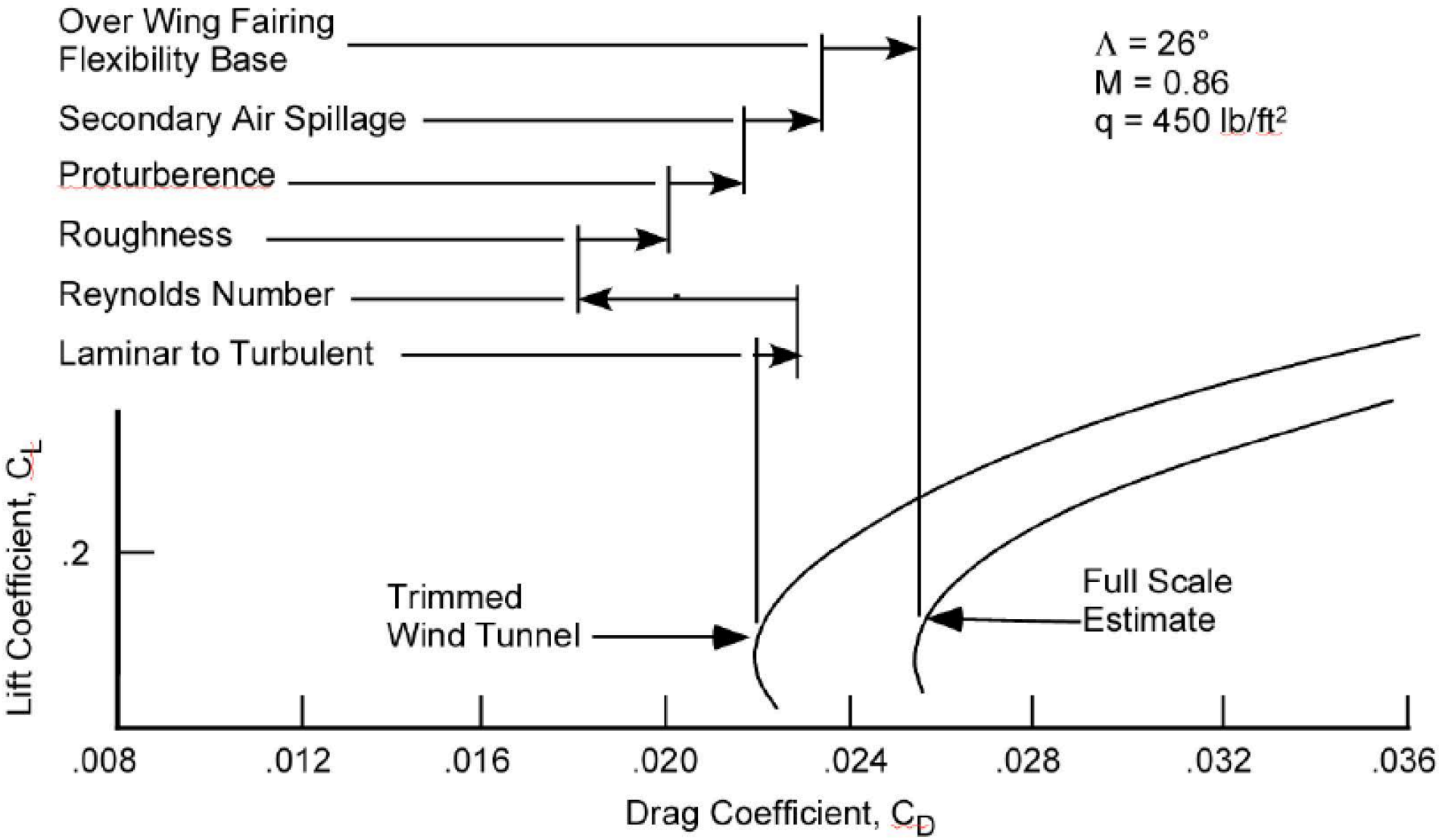
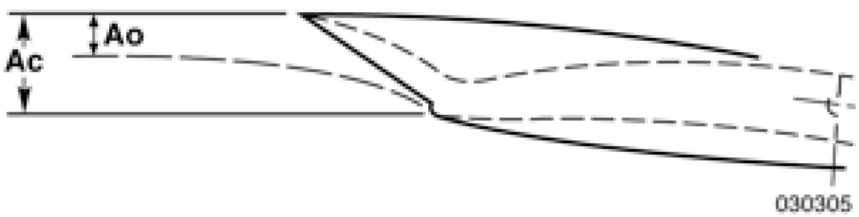


FIGURE 72 - ADJUSTMENTS MADE TO F-111 WIND-TUNNEL DRAG (AFFDL-TR-78-100)

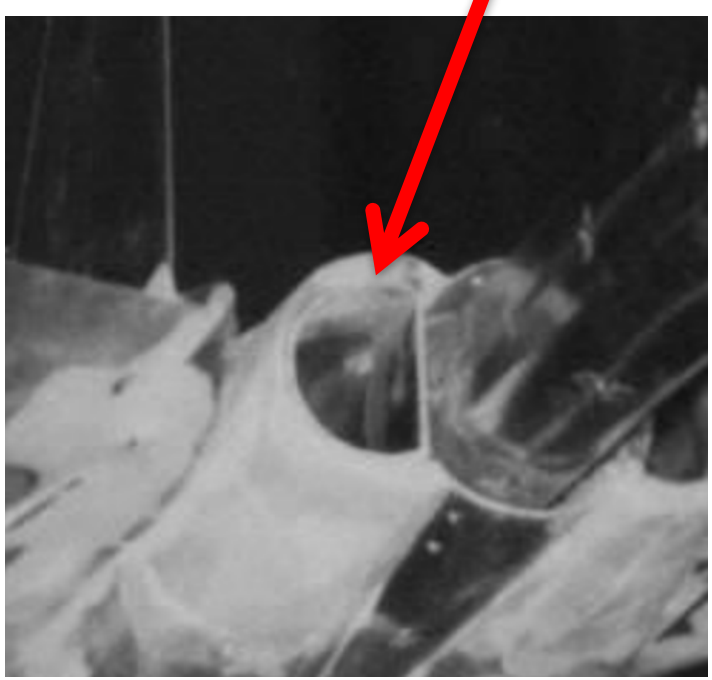
SPILLAGE DRAG CORRECTION

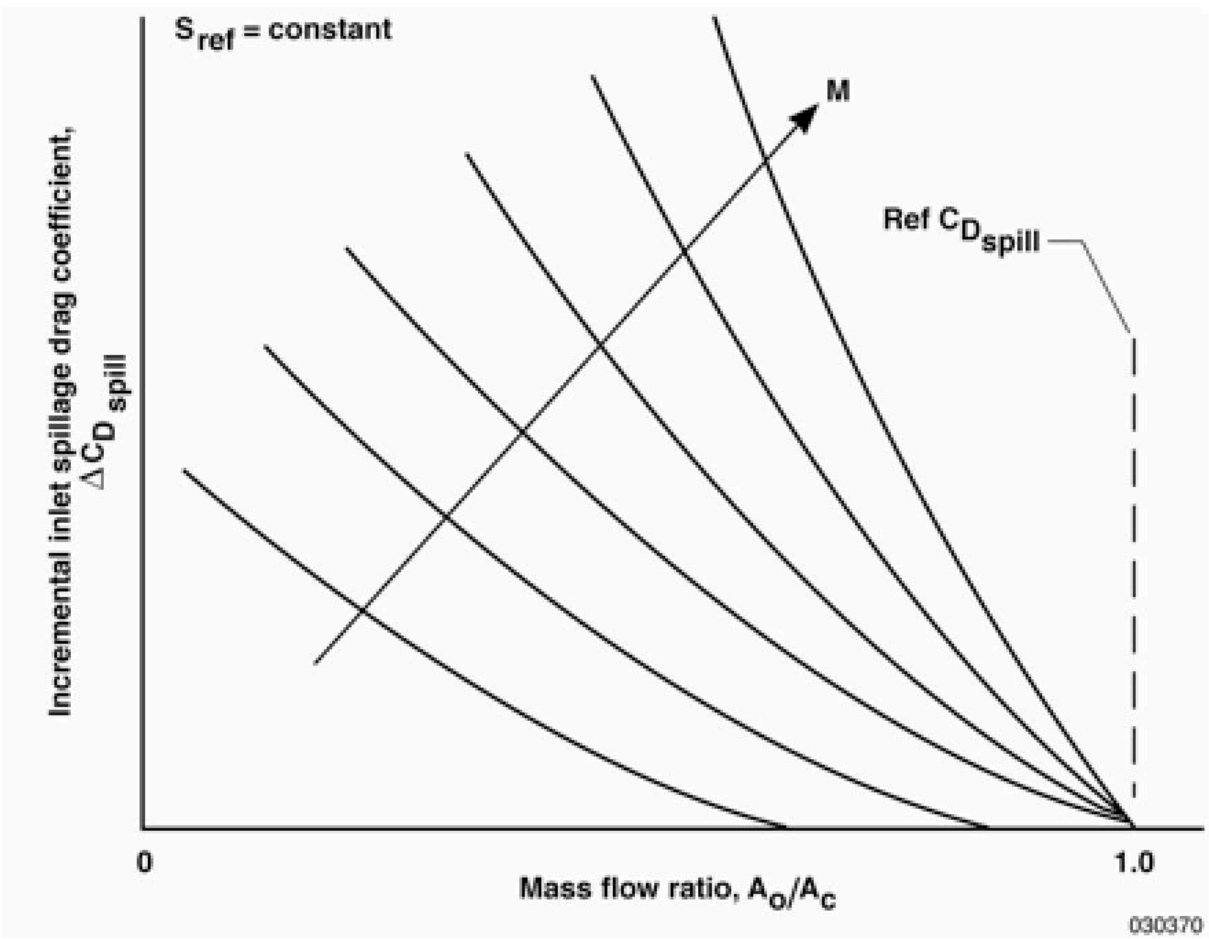
$$\left(\frac{A_o}{A_c}\right) = \frac{\text{Captured streamtube freestream area}}{\text{Inlet projected capture area}}$$



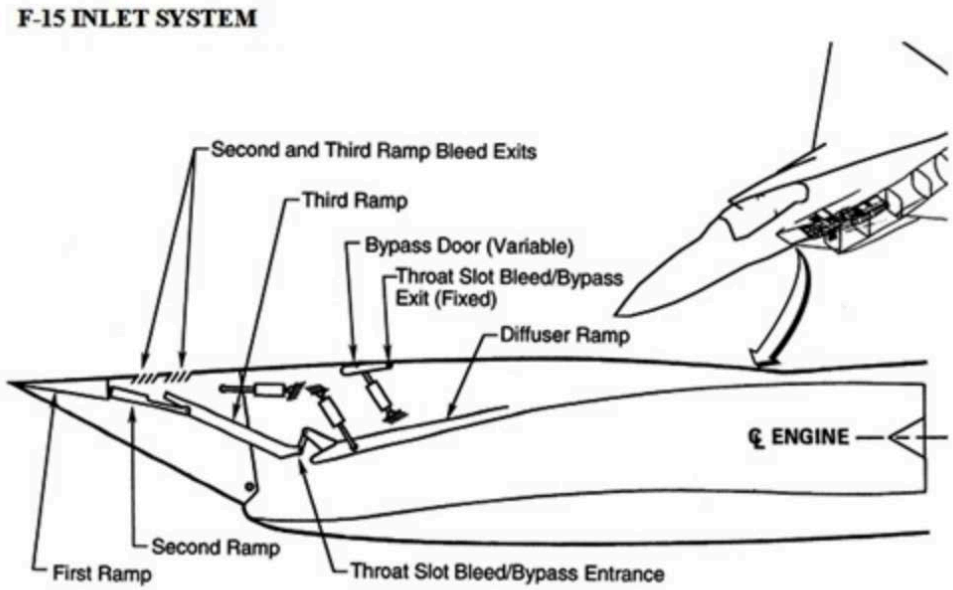
The throttle-dependent inlet spillage drag force increment is defined as the change in aircraft drag force resulting from the difference between operating and reference inlet mass flow ratios

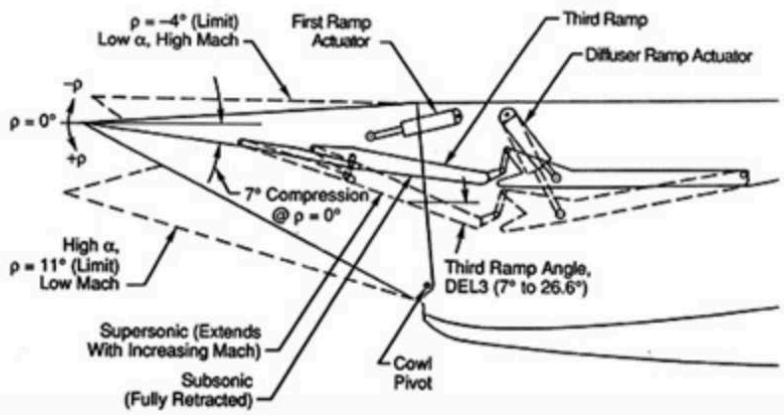
Inserts

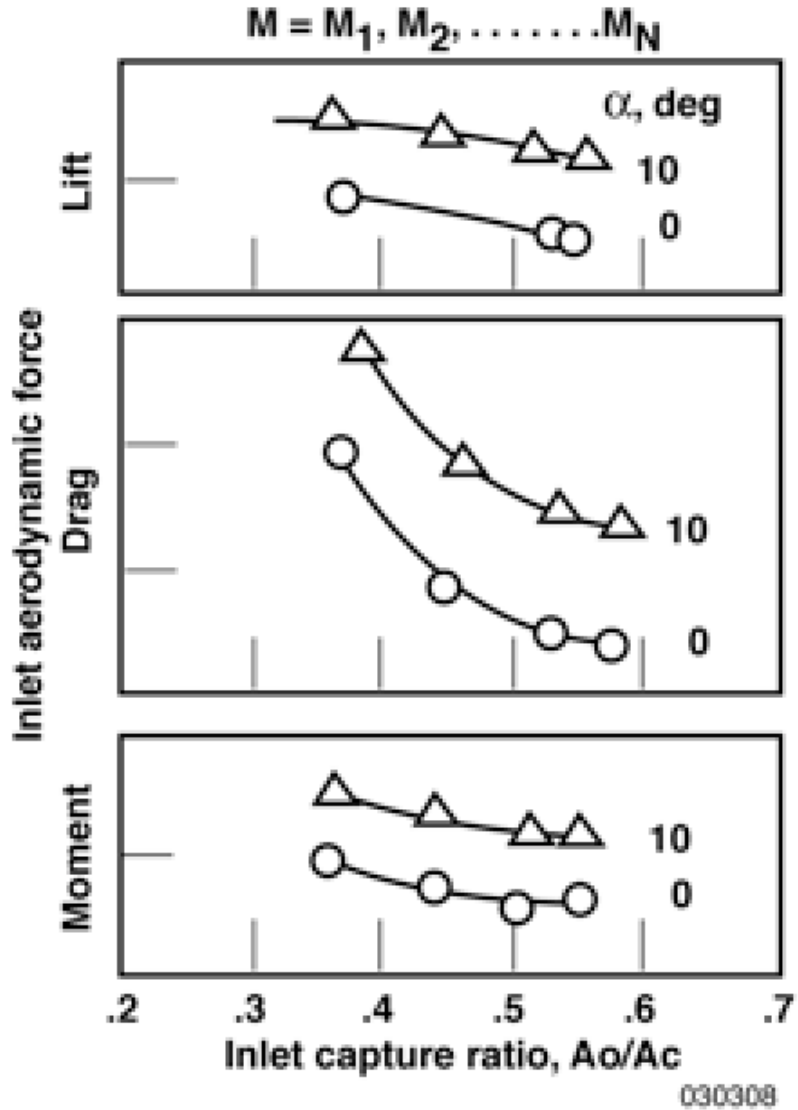




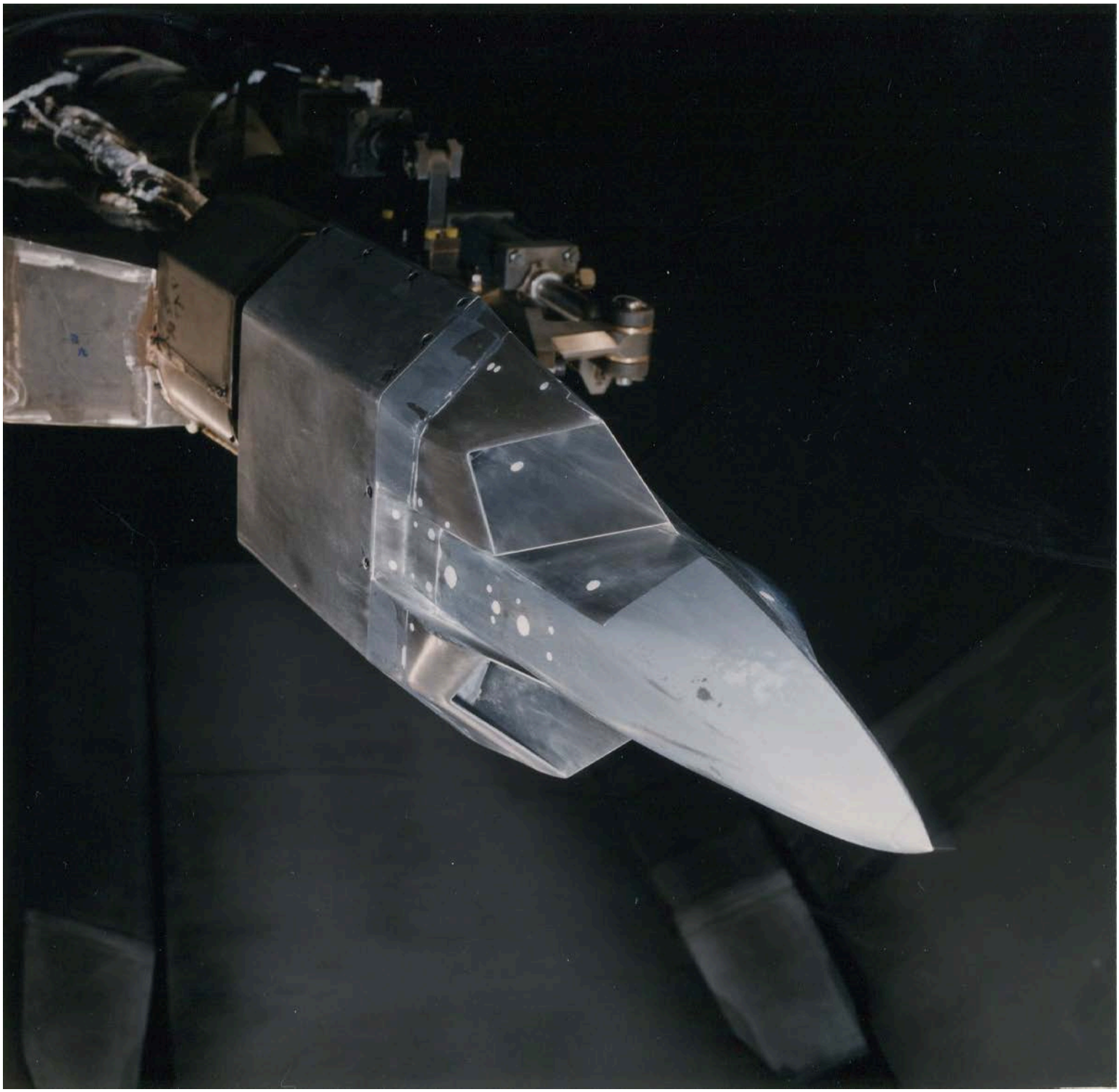
EXTERNAL INLET PERFORMANCE CORRECTIONS

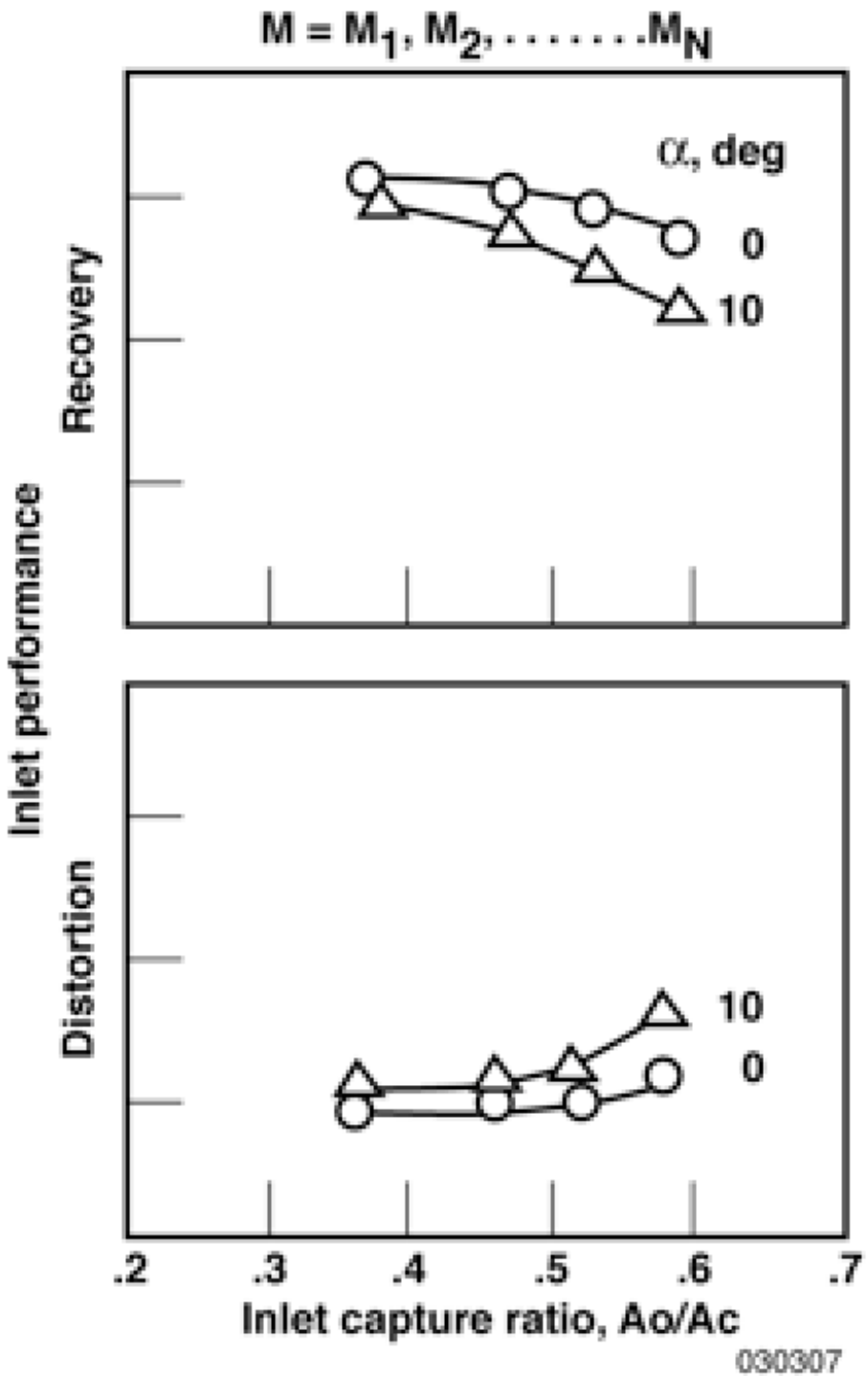






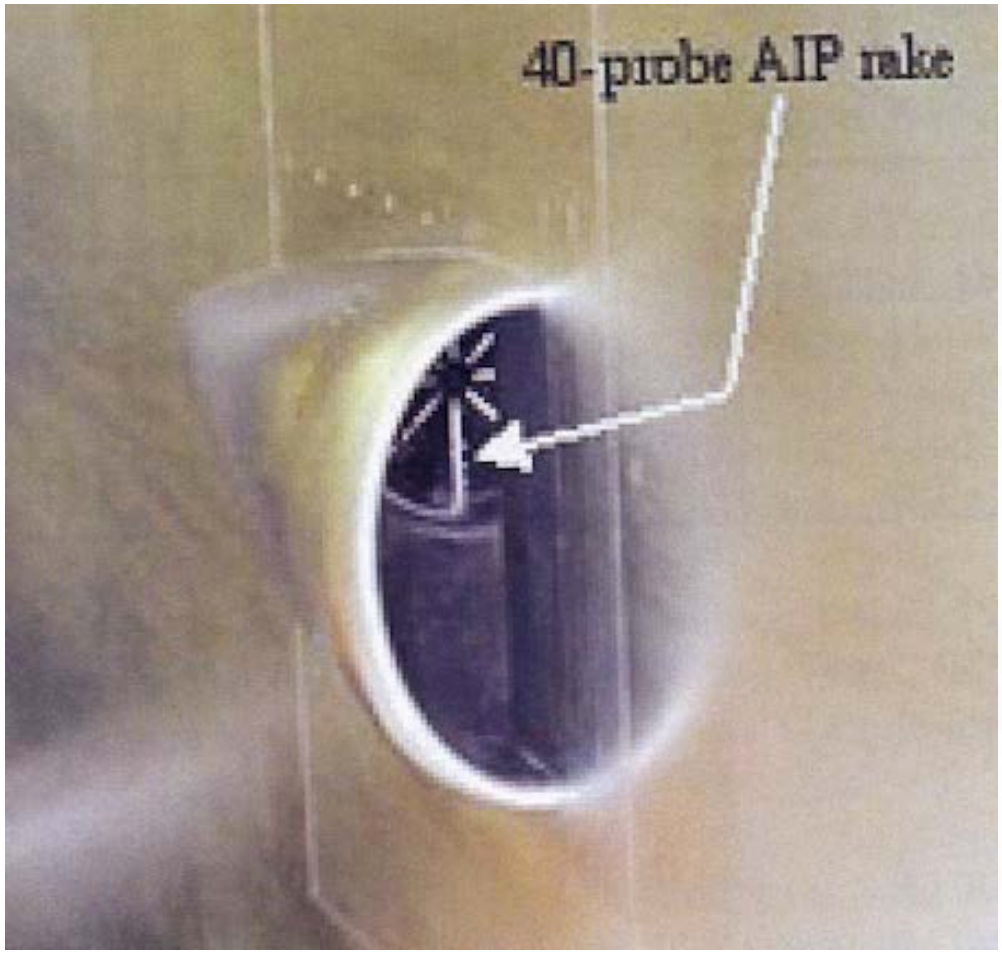
INLET MODEL

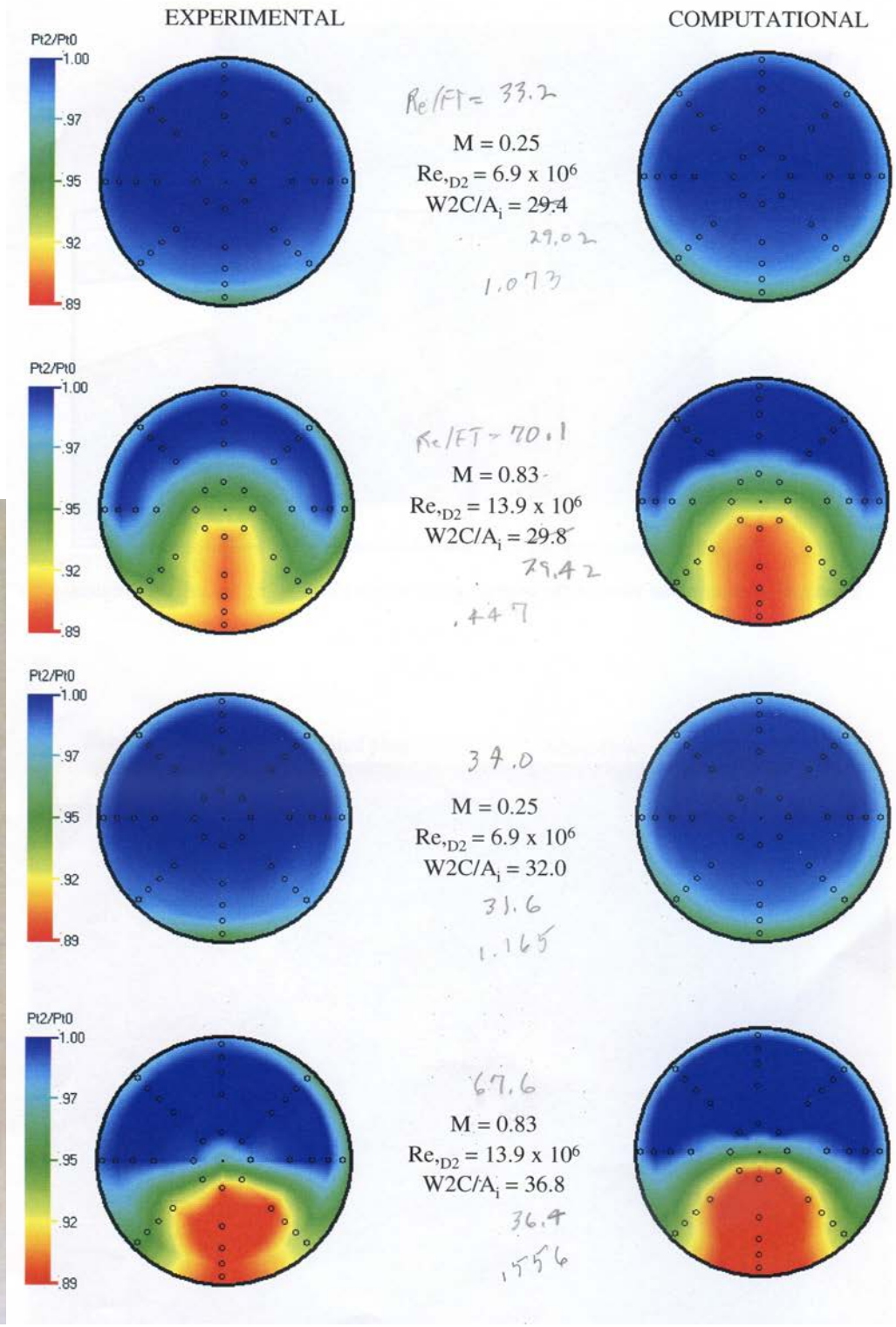




INTERNAL INLET PERFORMANCE

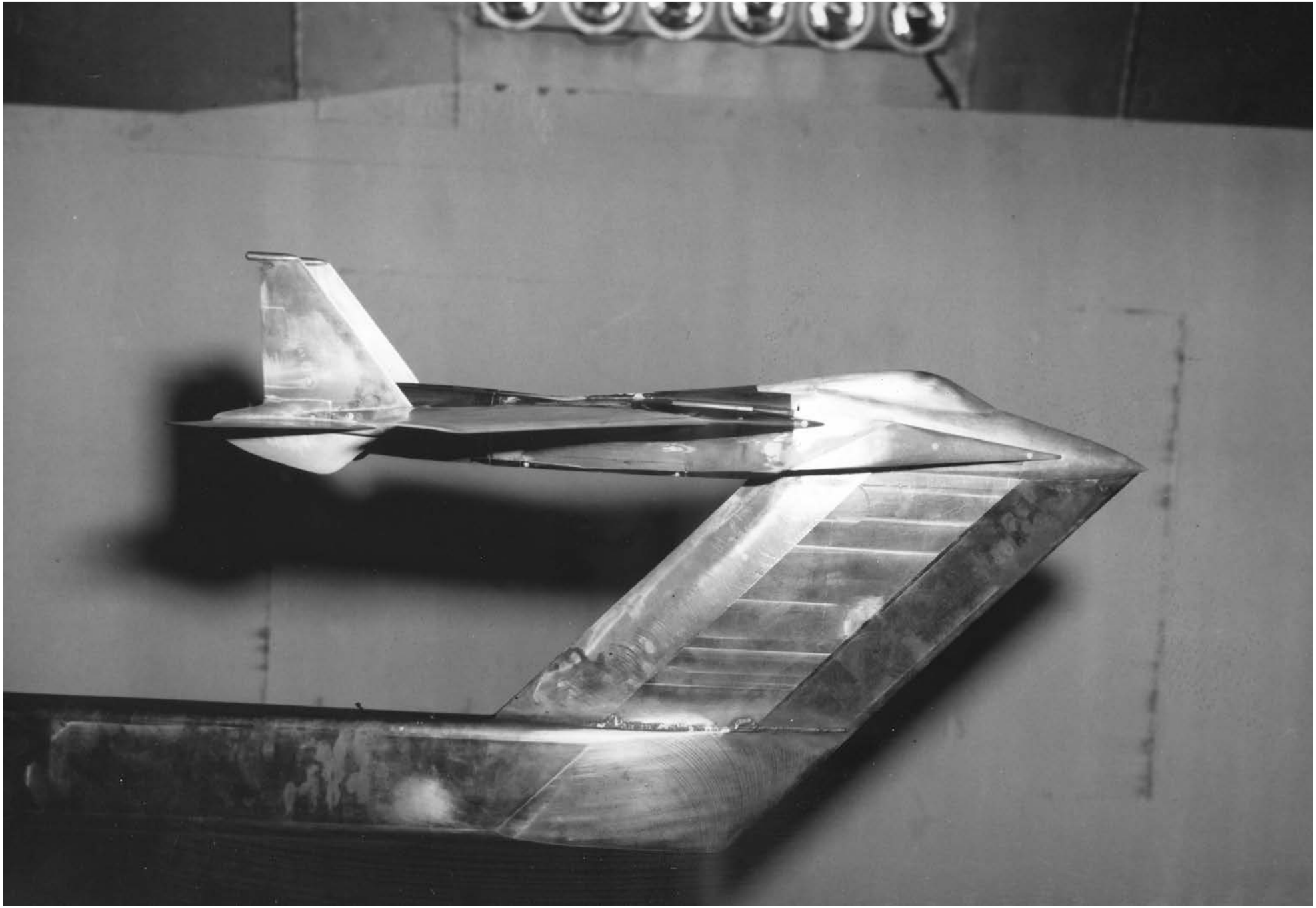
FAN FACE DISTORTION MAPS



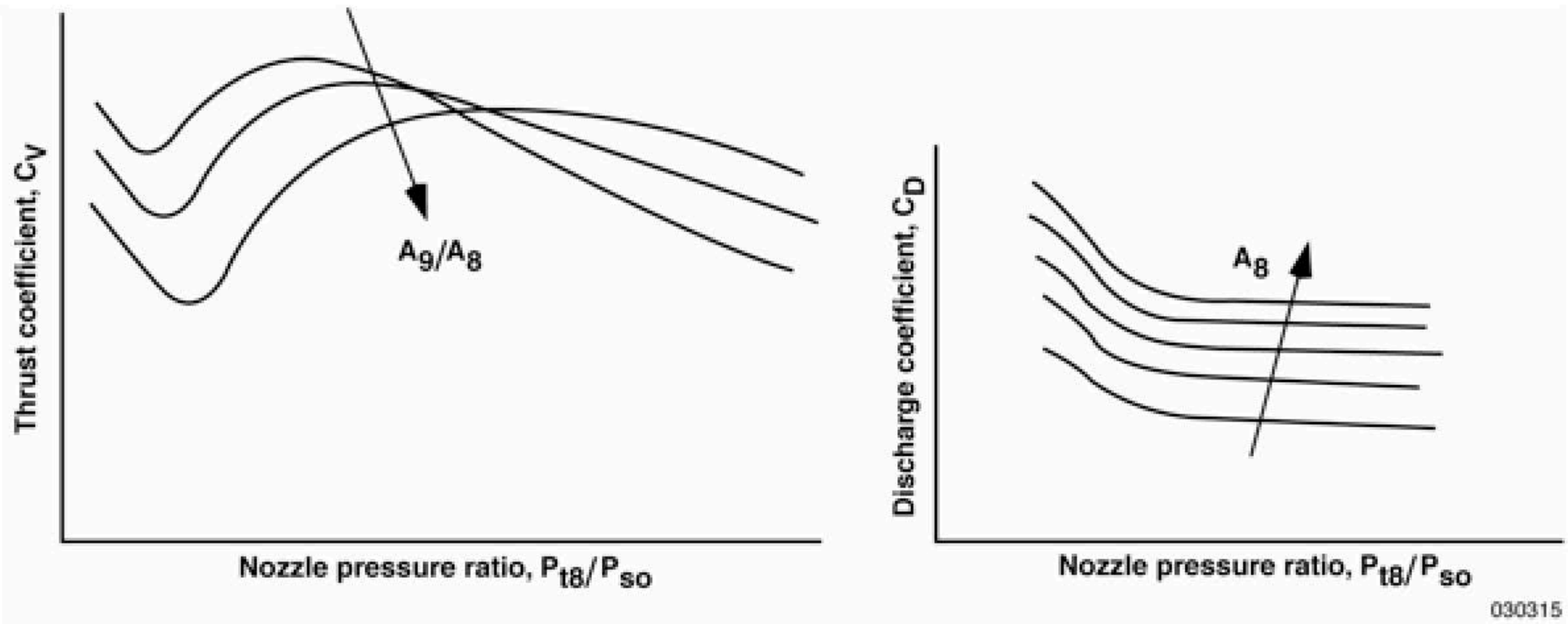


EXHAUST SIMULATION MODEL

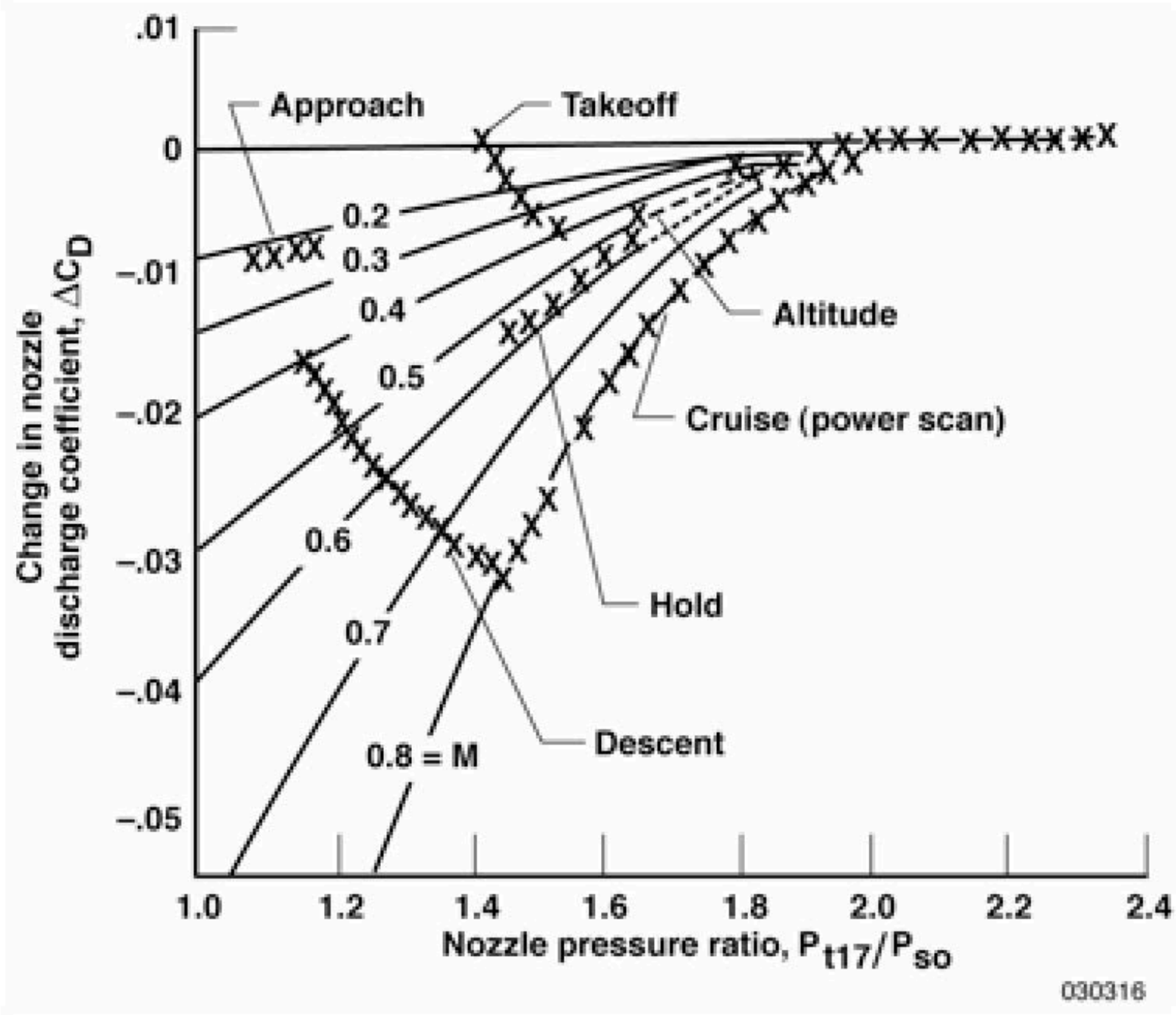
F-15 EXHAUST SIMULATION MODEL



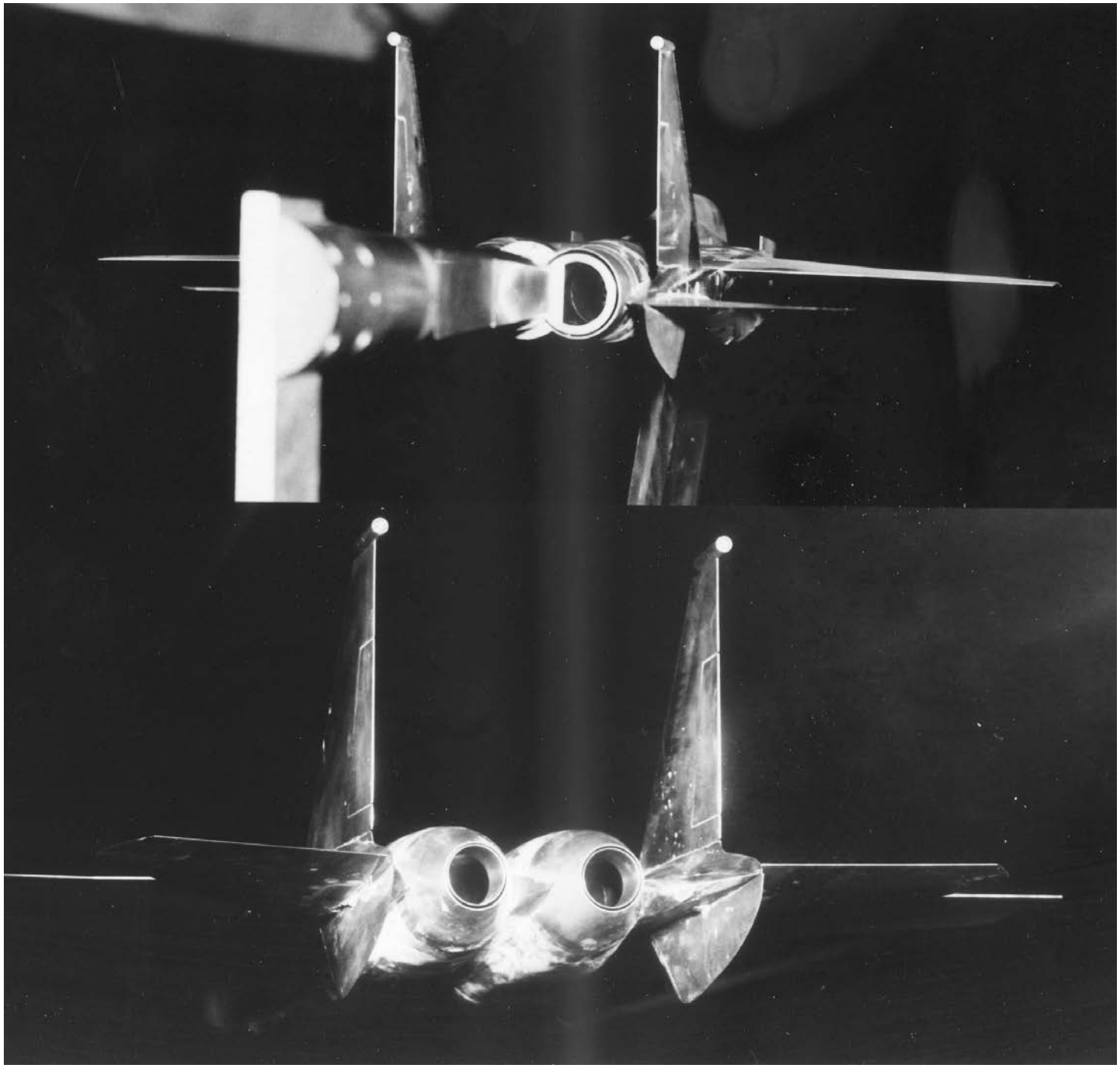
INTERNAL NOZZLE PERFORMANCE



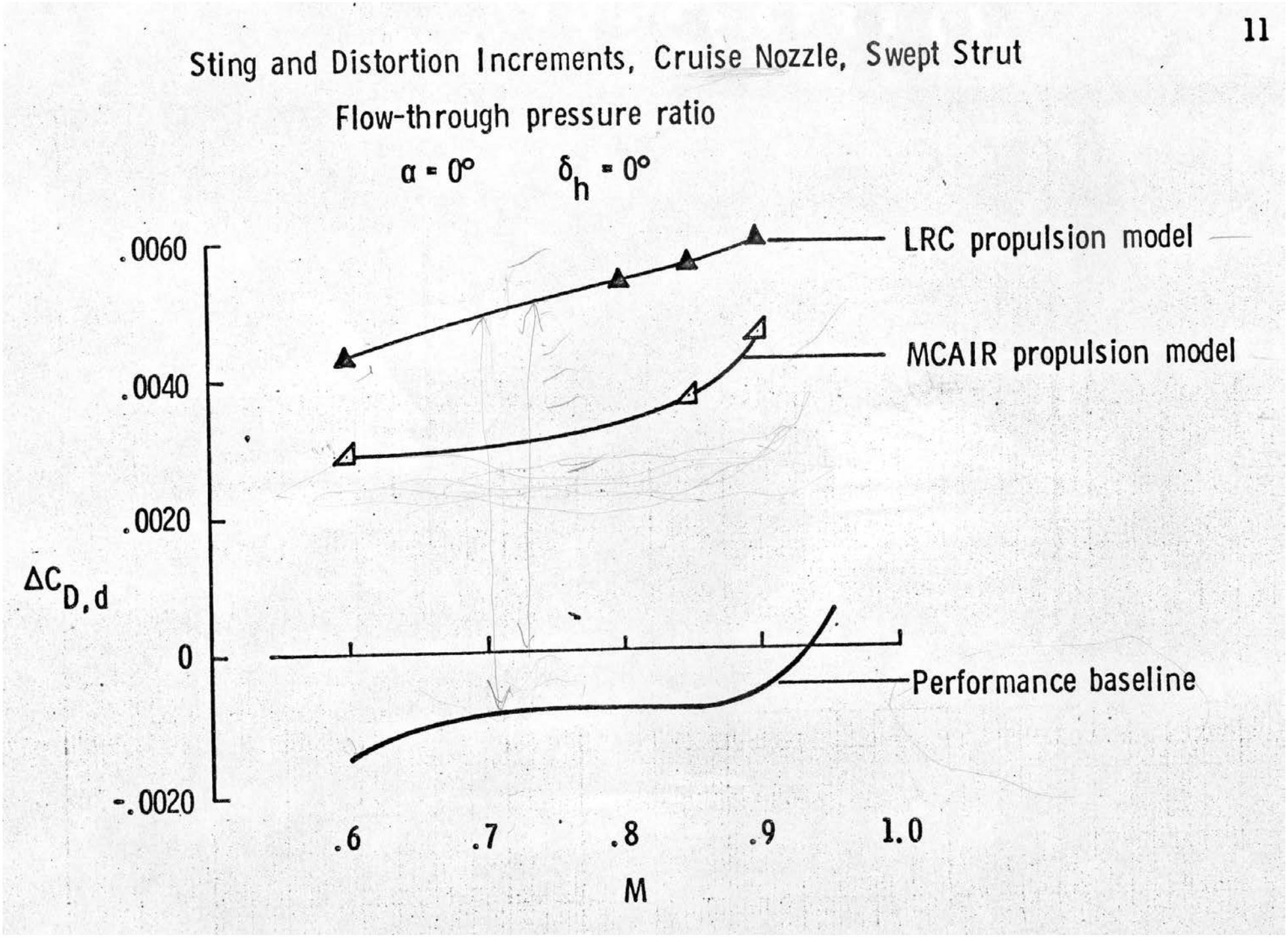
NOZZLE FLOW COEFFICIENT SUPPRESSION



STING AND DISTORTION CORRECTION MODELS



STING AND DISTORTION CORRECTIONS

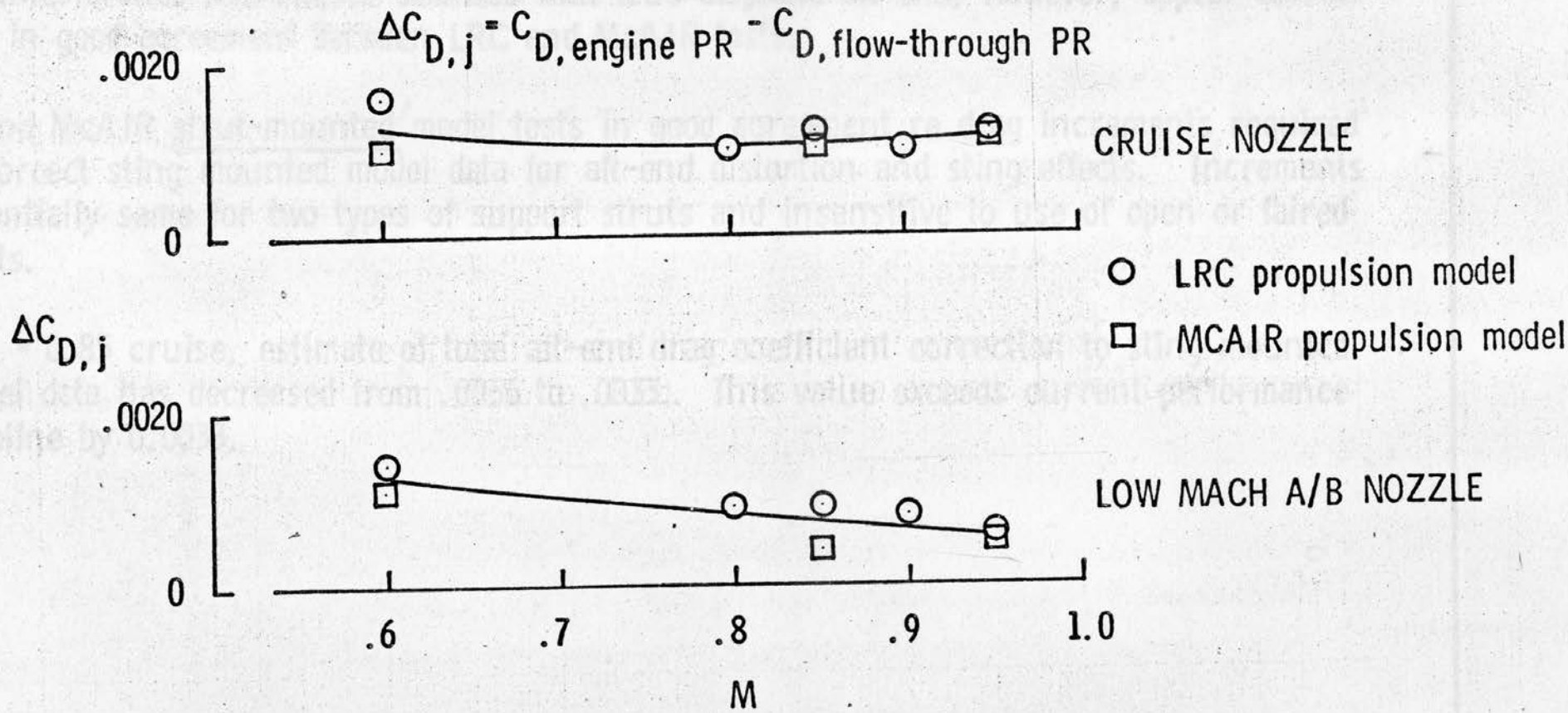


JET INTERFERENCE CORRECTIONS

JET INTERFERENCE INCREMENTS - SWEPT STRUT

Propulsion Model

$\alpha = 0°$ $\delta_h = 0°$



SOME REFLECTIONS ON AERODYNAMIC FORCE & MOMENT TESTING

Francis J. Capone
NASA Retired

April 17, 2017

AERODYNAMIC FORCE & MOMENT TESTING

OUTLINE

- MODEL SIZING/INSTALLATION
- BALANCES
  - Installation
  - Calibration
- STING DESIGN
  - Strength Characteristics
  - Sting Divergence
  - Interference Effects
- WEIGHT AND ATTITUDE TARES
- MODEL ATTITUDE
  - Importance
  - Basic equations
  - Tunnel Flow Angularity
- OTHER CORRECTIONS/ADJUSTMENTS
  - Base Pressure
  - Nacelle/Internal Duct Drag
- BOUNDARY LAYER TRANSITION
- OTHER CONCERNS

MODEL SIZING/INSTALLATION

HIGH-SPEED MODEL SIZING CRITERIA

- Model Cross-Sectional Size Dictated By Blockage (A_{model}/A_{tunnel}):
  - Subsonic speeds - $M < 1$
  - Supersonic speeds - $1.00 \leq M \leq 1.04$

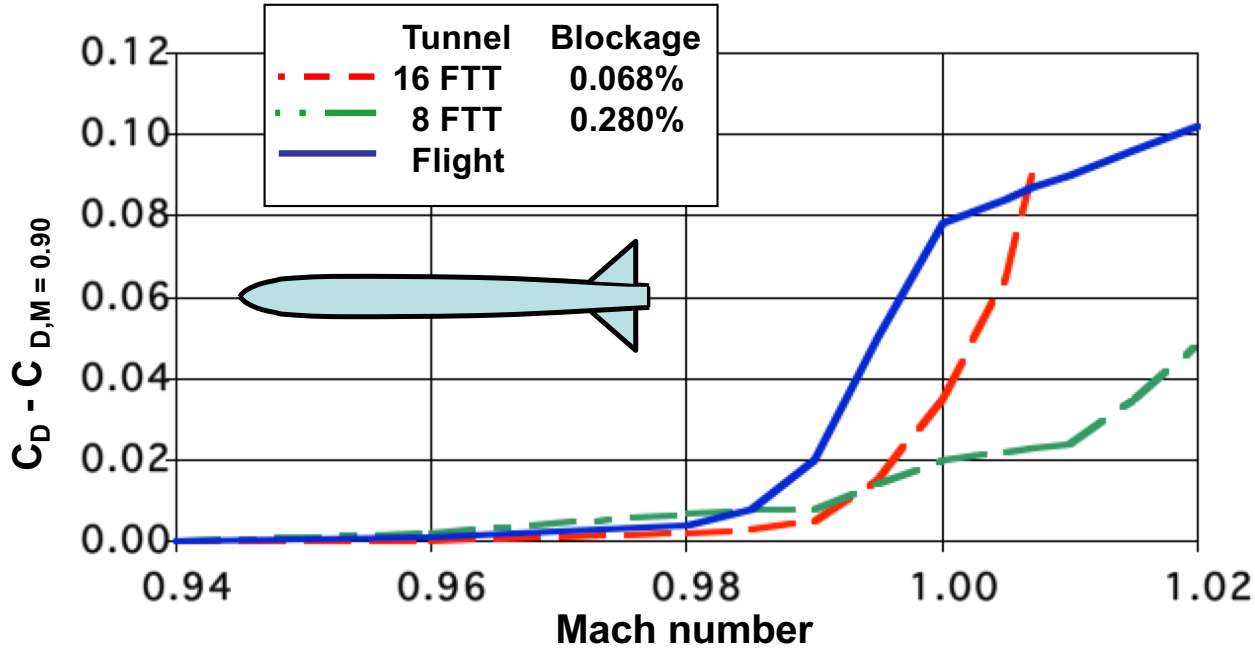
- Model Length Dependent On:
  - "Calibrated" test-section length at subsonic/supersonic speeds
  - Boundary reflected disturbances at supersonic speeds

- Model Volume:
  - Dependent if test section Mach number gradient sufficient to require buoyancy correction to drag coefficient (accepted gradient $dM/dL < 0.0006$)
  - Buoyancy correction = $f(\text{Volume})(dp_{ts}/dL)$

MODEL SPEED RANGE CONSIDERATIONS

- Model Flow Field/Wall Interference Effects Considered for the Following Mach Number Ranges:
  - M < 1.00 - Subsonic/Transonic blockage
  - M = 1.00 to 1.05 - Supersonic blockage
  - M > 1.05 - Shock reflections
- Results Presented Pertain to Wind Tunnels With Slotted Walls
- Blockage And Shock Reflection Criteria Derived From Specific Studies That Investigated These Problems

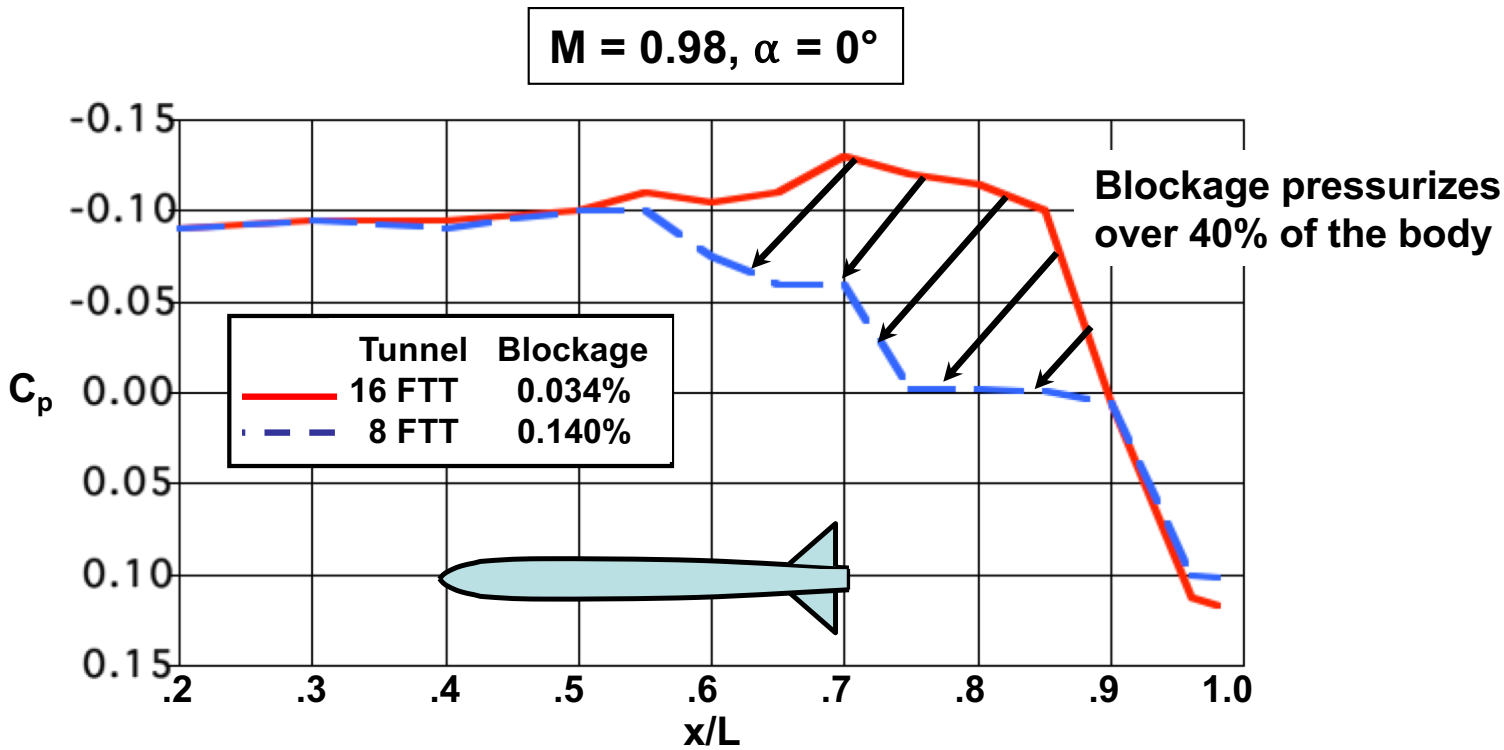
SUBSONIC BLOCKAGE INTERFERENCE



- Shown is a comparison of experimental to flight drag rise characteristics for the same supercritical body of revolution.
- Because of the very poor correlation of these results, a detailed study of blockage effects of thirteen bodies of revolution with four different profile shapes was initiated in both the 16-Ft Transonic Tunnel (16 FTT) and the 8-Ft Transonic Pressure Tunnel (8 FTT).
- All four body types exhibited the same drag characteristics as shown above, i.e., *drag* of the body was *significantly reduced* as *blockage ratio was increased*.

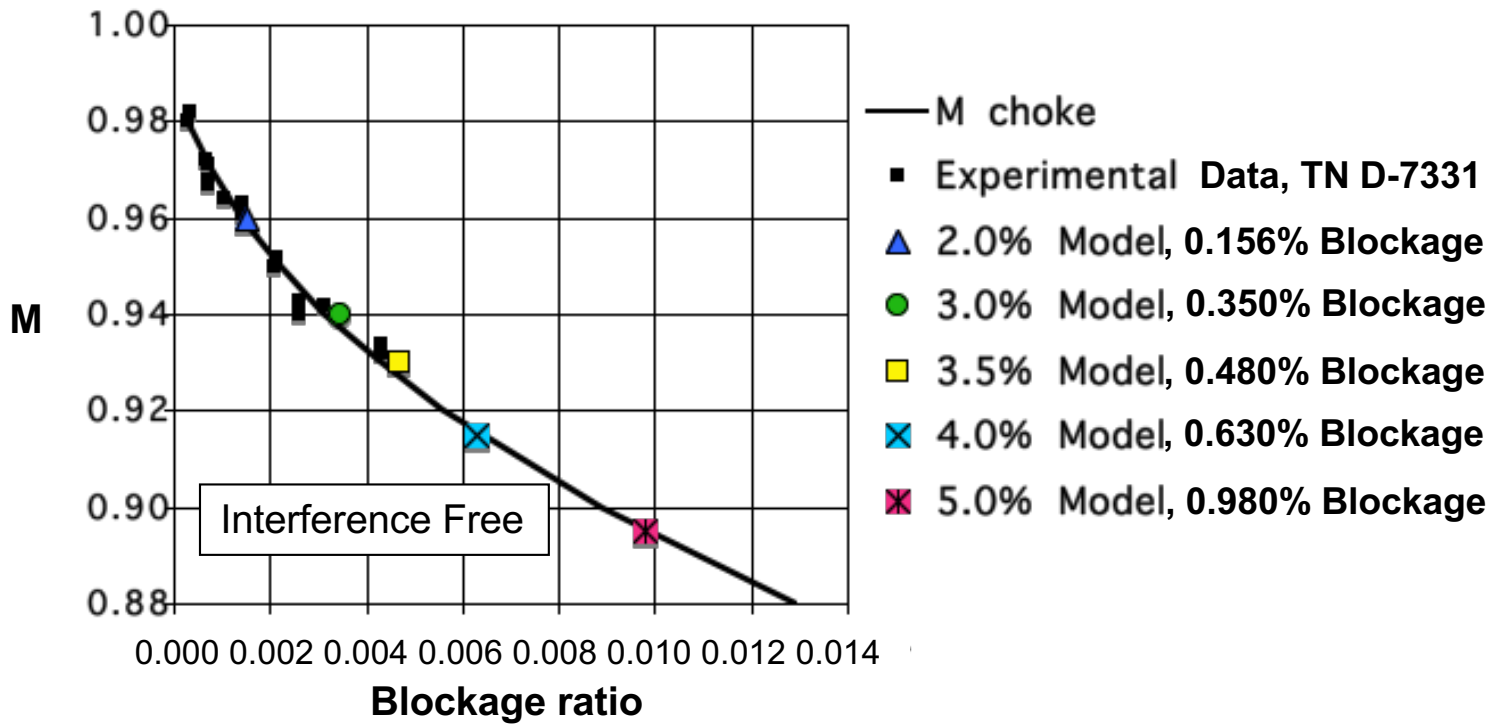
- **Couch and Brooks**: *Effect of Blockage Ratio on Drag and Pressure Distributions for Bodies of Revolution at Transonic Speeds*. NASA TN-D7331, 1973.

SUBSONIC BLOCKAGE EFFECTS ON BODY PRESSURE DISTRIBUTIONS



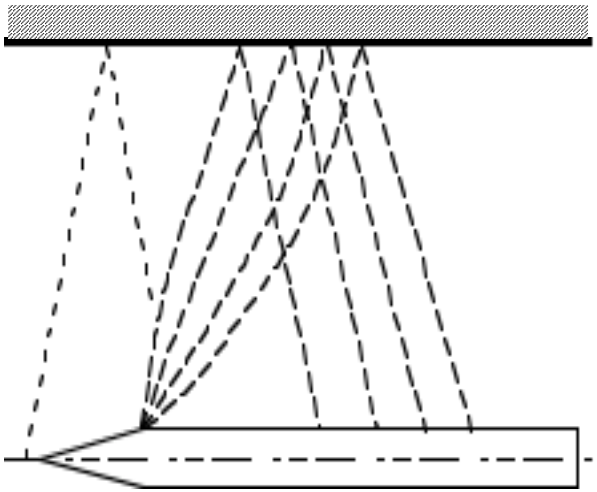
- One conclusion from NASA TN D-7331 was
  - "there was only one effect of wall interference on the model surface-pressure distributions obtained for a given model shape at different values of blockage ratio. An increase in blockage ratio for Mach numbers greater than 0.96 caused a positive increment of pressure to occur on the model"
- The net result of this increase in pressure was a decrease in drag.

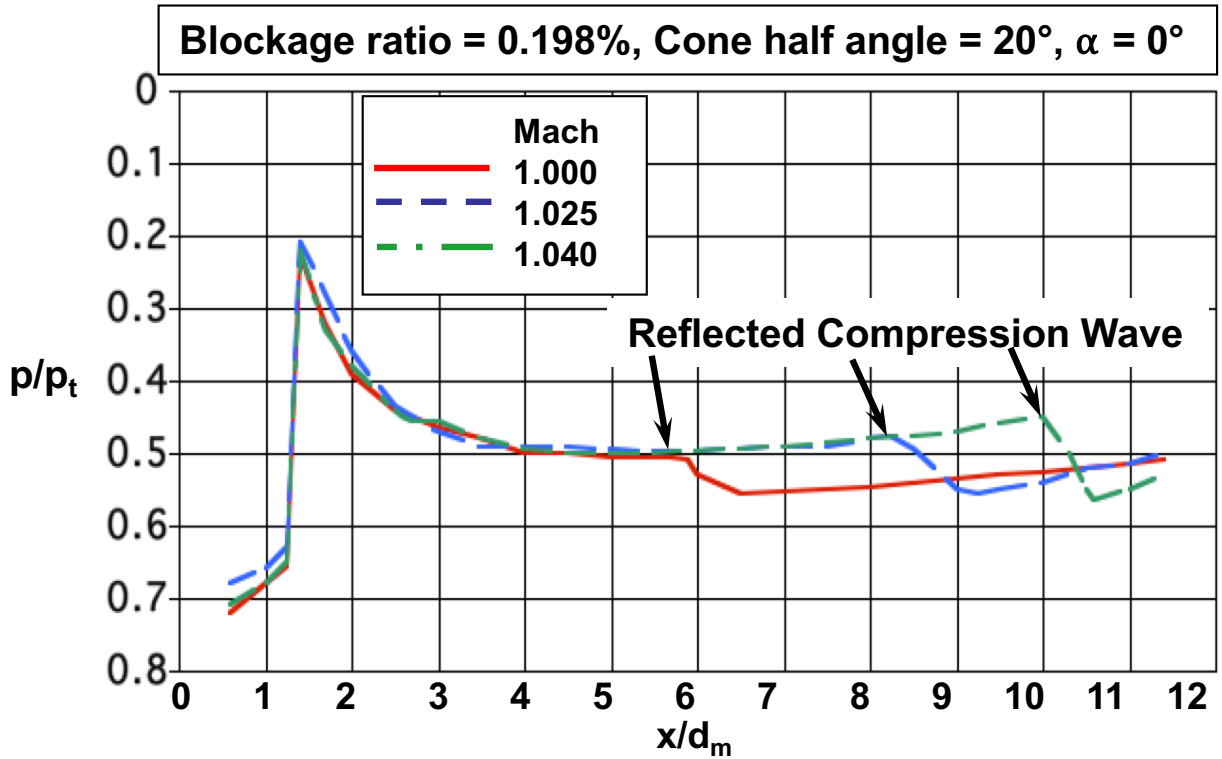
SUBSONIC BLOCKAGE CRITERIA



- NASA TN D-7331 also concluded that:
  - "increasing the blockage ratio above approximately 0.0003 produced a premature, positive deviation, or transonic creep, of the drag curve from the trend of the subsonic data. Since the Mach number at the initiation of the transonic creep agrees with the calculated Mach number for choked flow in a solid-wall tunnel, transonic creep may be the first indication of significant wind-tunnel wall interference near a Mach number of 1.0."
- This was the first investigation to indicate that the flow relief afforded by the test section slots - designed according to previously accepted criteria for interference-free subsonic walls - did not appear to be sufficient to avoid significant interference of the walls with the model flow field for Mach numbers close to 1.0.

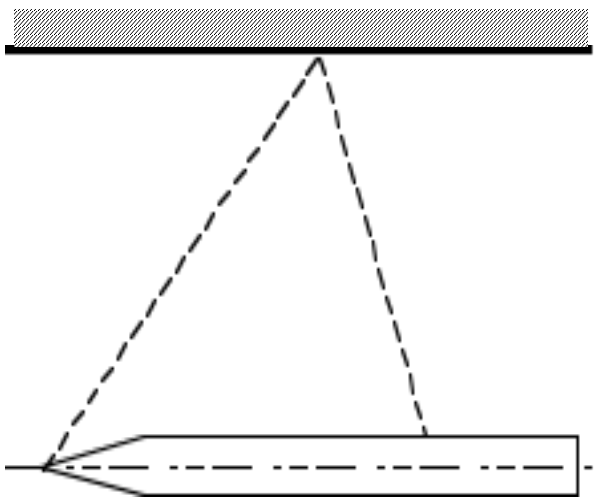
WALL INTERFERENCE IN SLOTTED WIND TUNNEL AT MACH NUMBERS FROM 1.00 TO 1.04

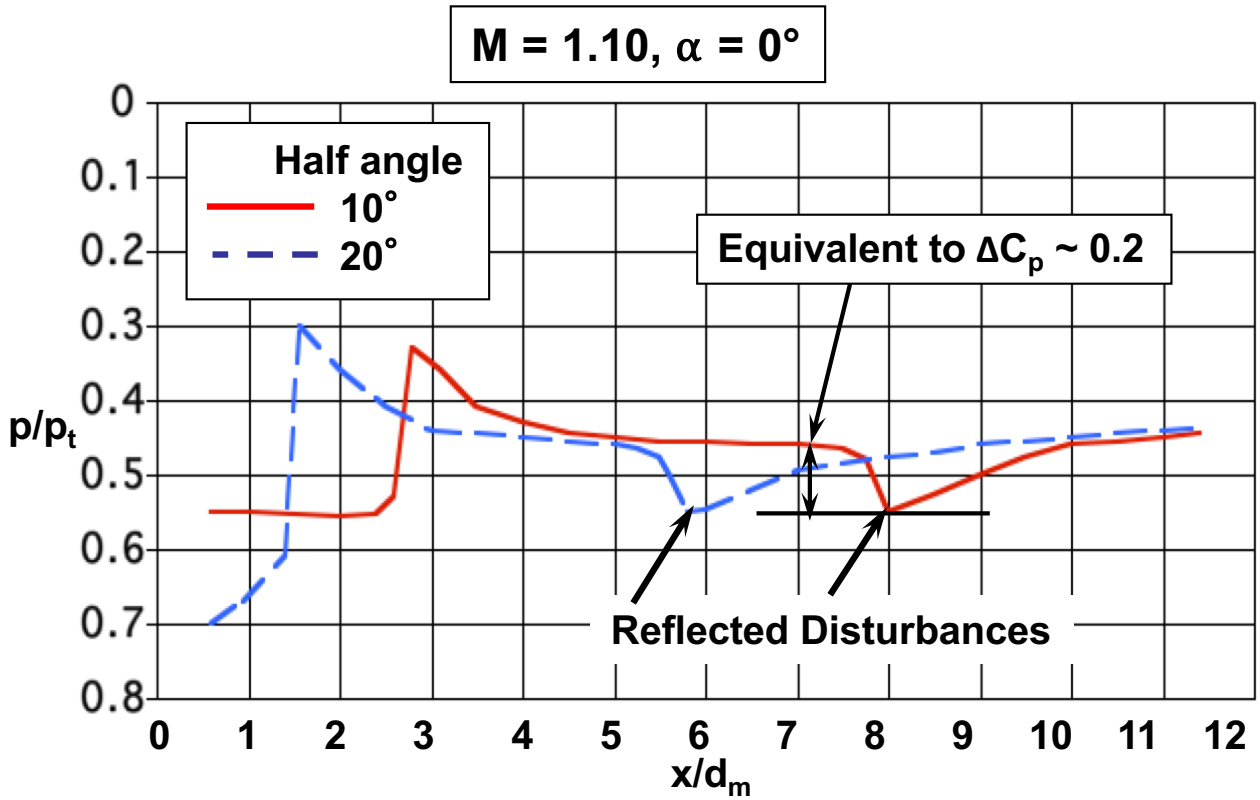




- Wall interference effects at these Mach numbers are dominated by reflection of the cone-shoulder expansion field being reflected back to the model as compression waves.
- The location of the reflected compression waves is dependent on the model blockage ratio.
- **Capone and Coates**: *Determination of Boundary-Reflected-Disturbance Lengths in the Langley 16-Foot Transonic Tunnel*. NASA TN D-4153, 1967.
- Similar results reported in NACA TN 4233 and AEDC-TR-59-12 (perforated walls).

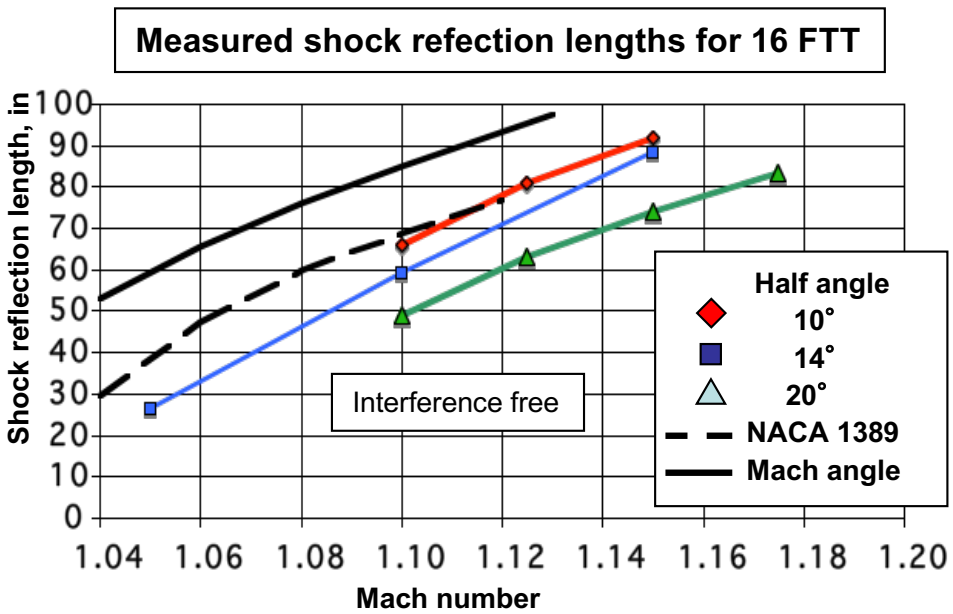
SHOCK REFLECTION CHARACTERISTICS FOR SLOTTED TUNNELS

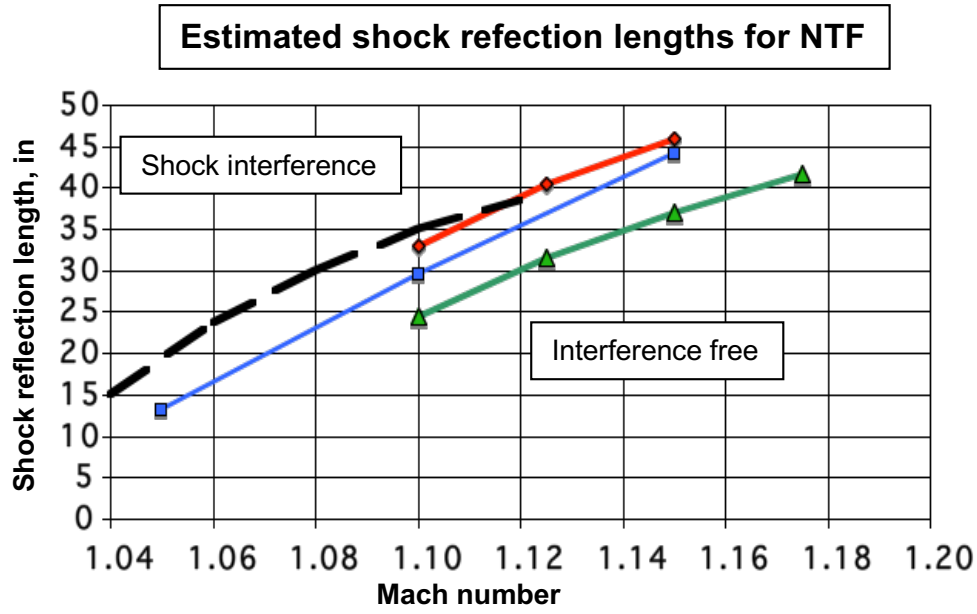




Wall interference effects at Mach > 1.05 are dominated by impingement of boundary-reflected-disturbances (reflected bow shock) on the model.

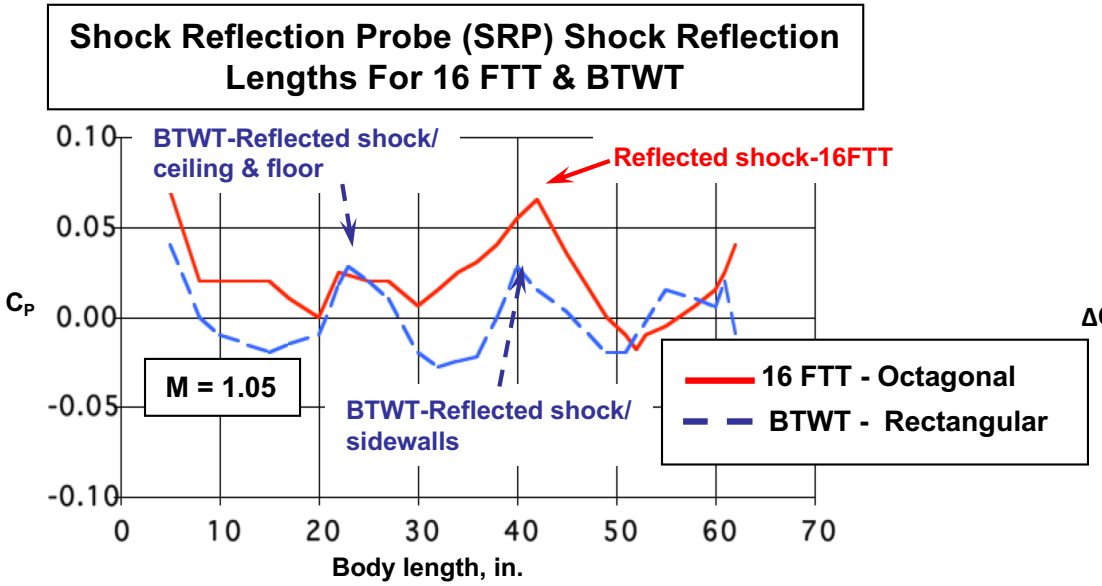
SHOCK REFECTION LENGTH CRITERIA FOR SLOTTED TUNNELS

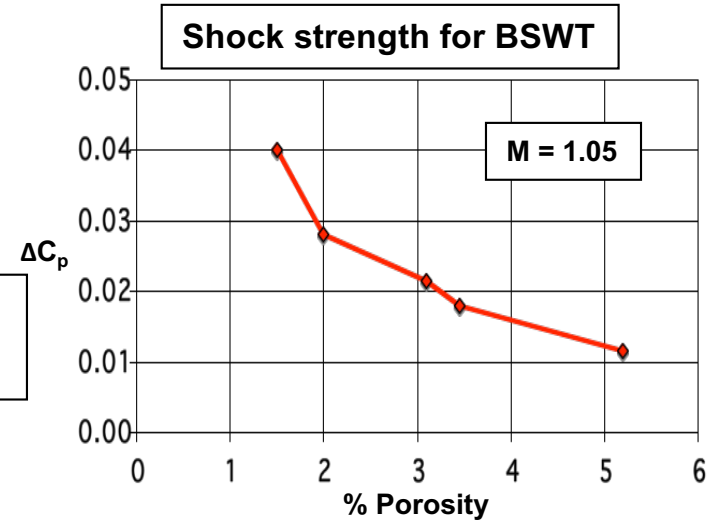




- Results indicated that the stronger the bow shock wave, the shorter the maximum interference-free model length.
- Shock reflection lengths determined from the Mach angle are much longer than those measured.
- The dashed line represents the average shock reflection lengths measured in the original 12-sided 8 Ft. tunnel (NACA Rpt. 1389) using a body with a nose half angle approximately 10°.
- Results for additional configurations can be found in NASA TN D4152 and NASA/TM-1998-208723. The body used in the latter reference approximated the fuselage of a supersonic transport.

COMPARISON OF REFLECTED SHOCK CHARACTERISTICS FOR SLOTTED AND PERFORATED TUNNELS



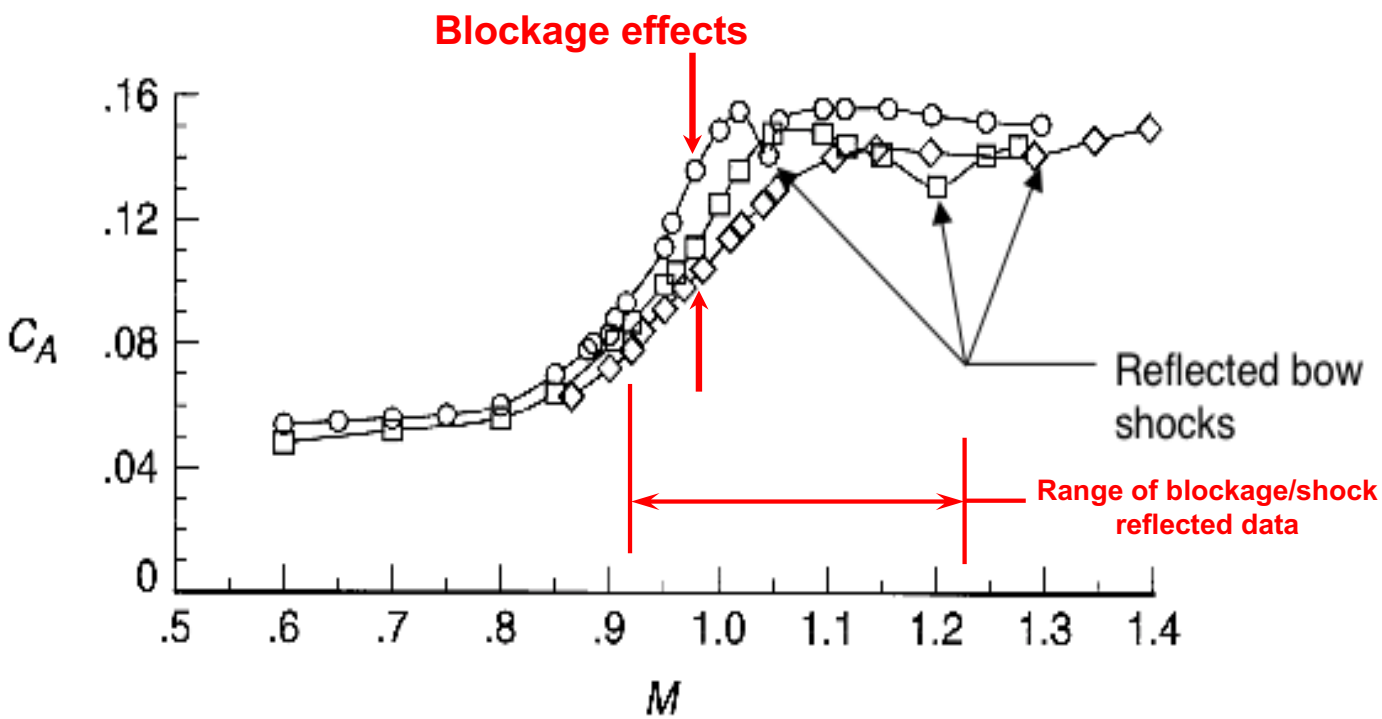


- A body of revolution with a nose shape that produces a bow shock of approximately the same strength as a realistic HSCT configuration was tested in the:
  - Langley 16-FTT slotted octagonal test section
  - Boeing BTWT 8x12 slotted rectangular test section
  - Boeing BSWT 4 foot perforated test section insert
- A conclusion from AIAA-94-1935 was " The long standing rule to **not test when reflected shocks impinge on a model** is valid and appropriate for slotted-wall test sections; slotted walls **do not provide significant attenuation of shocks**."
- Another conclusion from AIAA-94-1935 was "**Any force, moment, and pressure data** obtained at low supersonic Mach numbers **should be viewed with caution when shock reflection occur** on a model, since **shock reflections significantly affect the flow**."
- **REFERENCES:** NASA/TM-1998-208723, October, 1998. AIAA-94-1935, June, 1994.

BLOCKAGE & SHOCK REFLECTION EFFECTS ON SHUTTLE AXIAL FORCE

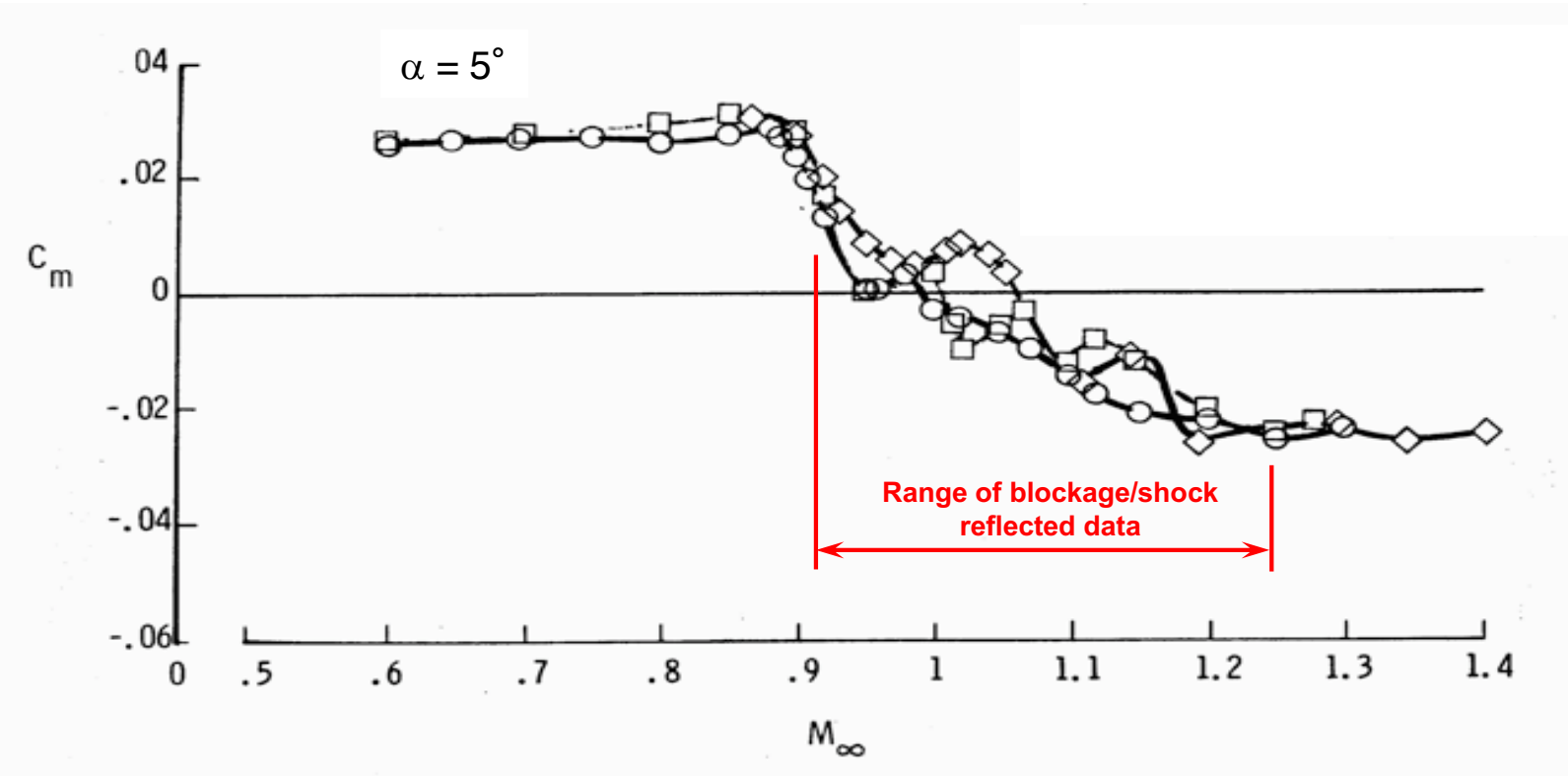
	Blockage Ratio	Model Scale	Tunnel	Max $M_{inter\ free}$
○	0.0008	2 %	LaRC 16 Ft	0.95
□	0.0053	5 %	LaRC 16 Ft	~0.90
◇	0.0114	5 %	ARC 11 Ft	??

Max M based on NASA TN D-7331



BLOCKAGE & SHOCK REFLECTION EFFECTS ON SHUTTLE PITCHING MOMENT

	Blockage Ratio	Model Scale	Tunnel	Max $M_{inter\ free}$
○	0.0008	2 %	LaRC 16 Ft	0.95
□	0.0053	5 %	LaRC 16 Ft	~0.90
◇	0.0114	5 %	ARC 11 Ft	??



TEST SECTION *"LENGTH"*

- Once a model length is known, it is necessary to take a look at the length of the test section available at the highest Mach number planned for the test. Is it adequate for the model to be positioned properly longitudinally?

- For example, test section length was dependent on Mach number in the 16-Foot Transonic Tunnel
  - Maximum model length = 25 feet for M < 1
  - Maximum model length = 8 feet for M = 1.20
  - Maximum model length = 10 feet for M = 1.30

- If the model is outside calibrated test section, are buoyancy corrections required?

FORCE BALANCES

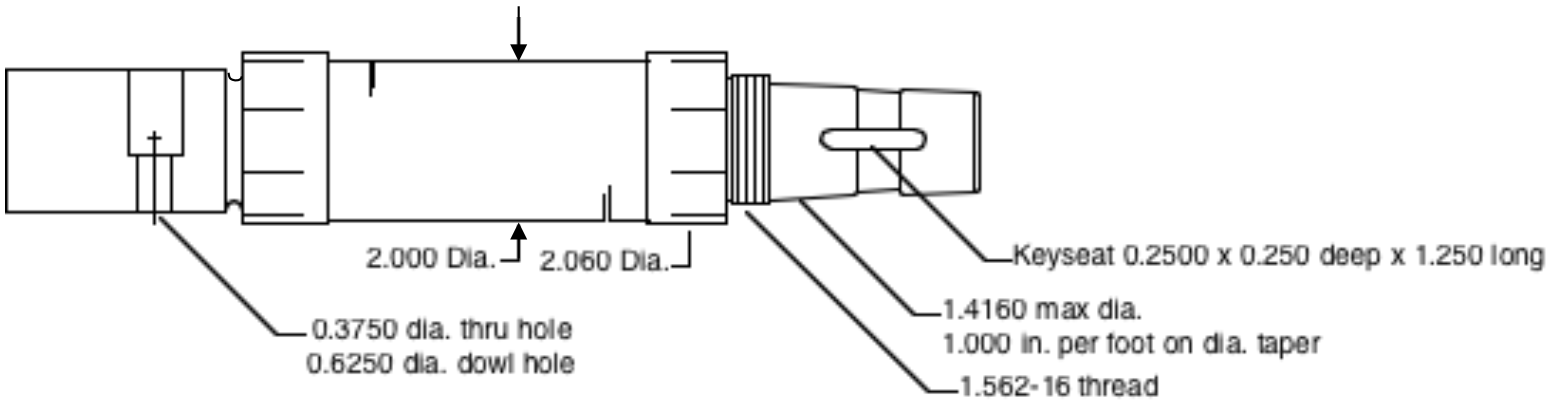
SOME GENERALITIES ABOUT FORCE BALANCES

- Langley
  - Fabricated from a single piece of metal
  - Flexible for greater output resolution
  - Temperature compensated for modulus change
  - Combined load calibrations
  - Performance documented over time by instrumentation technicians

- Task
  - Assembled from parts (floating frame construction)
  - More rigid than langley balance for same load range
  - Often not compensated for modulus change with temperature
  - Some contain thermocouples for computing modulus temperature effects
  - Can have internal mechanical stops (for safety) unknown to user
  - Should be completely calibrated at Langley over planned test range unless customer supplied documentation satisfactory

- Other
  - Boeing balances usually perform well

TYPICAL LANGLEY FORCE BALANCE



1621	
Component	Loads
Normal	3000 lb
Axial	500 lb
Pitch	10,000 in-lb
Roll	7500 in-lb
Yaw	4500 in-lb
Side	1800 lb

1630	
Component	Loads
Normal	3000 lb
Axial	800 lb
Pitch	10,000 in-lb
Roll	7500 in-lb
Yaw	4500 in-lb
Side	1800 lb

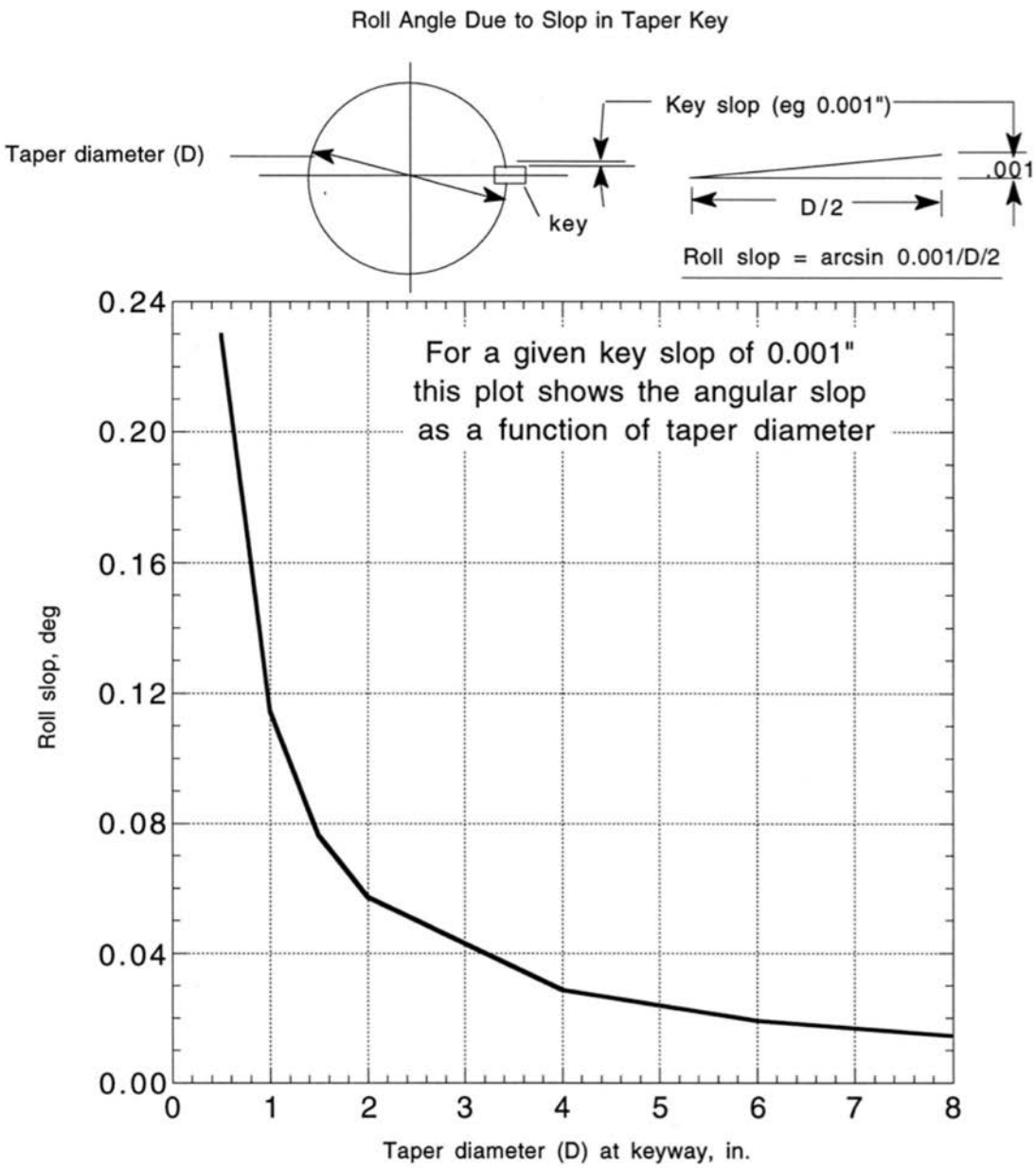
PREPARATION FOR TESTING - BALANCE INSTALLATION

- Balance Fit:
  - Check fit of balance to model balance-block
  - Provide custom made tight fitting balance-to-model block pin(s)
  - Check taper surface contact between balance and sting tapers
  - Provide tight fitting roll key for use in balance-to-sting tapers
  - Check to see that the balance-to-sting roll key length or height does not prevent balance taper from seating
  - Use AMS units to document quality of fits of assembled support hardware
  - After all tubes and leads passed through sting, plug sting passage with clay

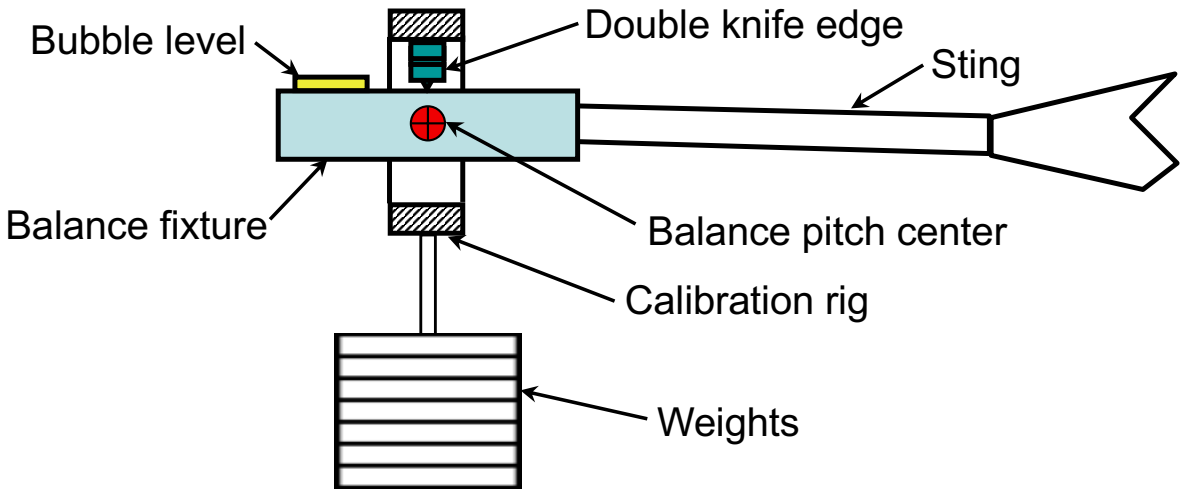
- Pre-Model Continuity Checks:
  - Before model buildup when balance taper and mini-plug are accessible, hand load all balance components through the DAS

- Balance/Model Loadings In Tunnel/Model Buildup Bay
  - Determine balance/sting deflection constants (backup/alternate to model attitude transmitter measurements
  - Determine restraint effects on balance readings due to tubes, leads, etc.
  - Assure adequate metric/nonmetric clearances under load (foul-free setup)
  - In-tunnel check loads to verify force measuring system as installed

ONE SOURCE OF ERROR IN α MEASUREMENT



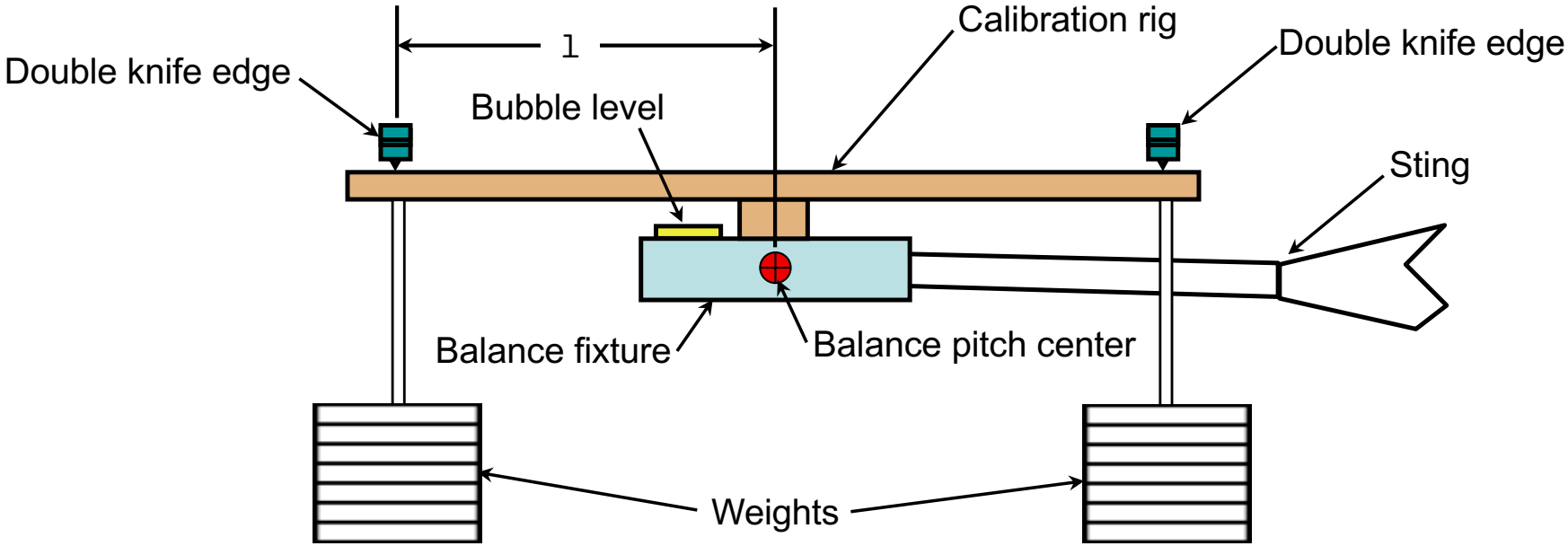
BALANCE FORCE CALIBRATION



NOTE:
1. Level balance fixture between loadings
2. Roll sting and balance 180° at sting coupling to get negative force calibration

PREFERRED BALANCE MOMENT CALIBRATION

Moment = $l(\Delta\text{weight})$

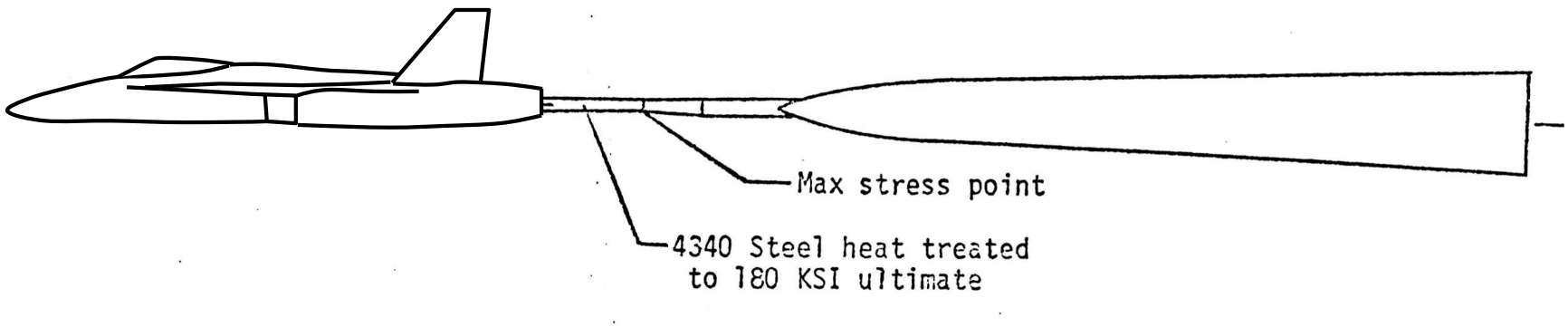


NOTE:

1. Moment obtained by shifting weights
2. Level balance fixture between loadings
3. Roll sting and balance 90° at sting coupling to make yaw calibrations

STING DESIGN

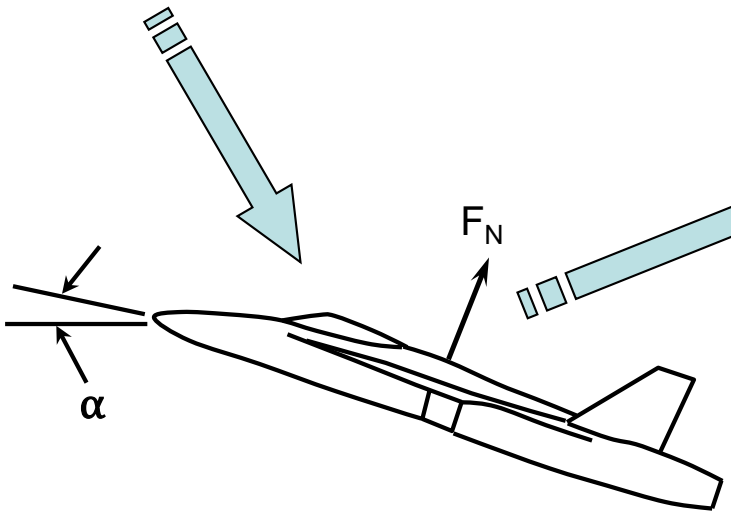
STING DESIGN - STRENGTH

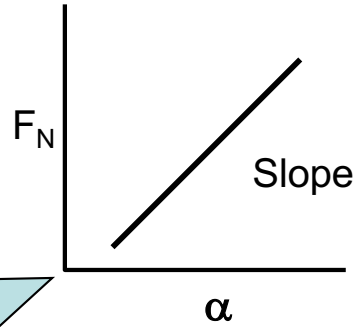


Mach Number	α, deg	Max Stress, psi	Allowable Stress (1/4 ultimate)
0.6	0	19,634	45,000
0.8	0	20,286	
0.9	-2	39,237	
0.9	0	20,339	
0.9	6	42,947	
1.0	0	18,508	
1.1	0	19,058	
1.2	0	18,785	
1.3	0	17,838	

STING DIVERGENCE CRITERIA

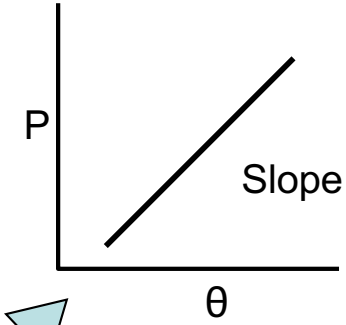
M	α	L	D



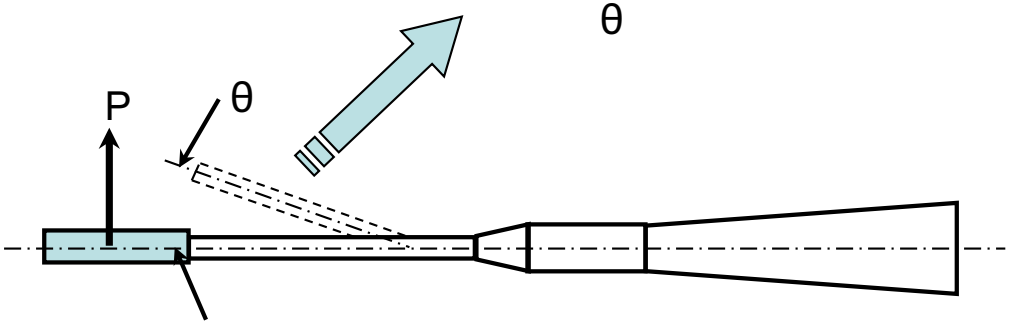


$$\text{Slope} = \frac{\Delta F_N}{\boldsymbol{\Delta\alpha}} = C_{N\alpha}(\theta)S \ \#/^\circ$$

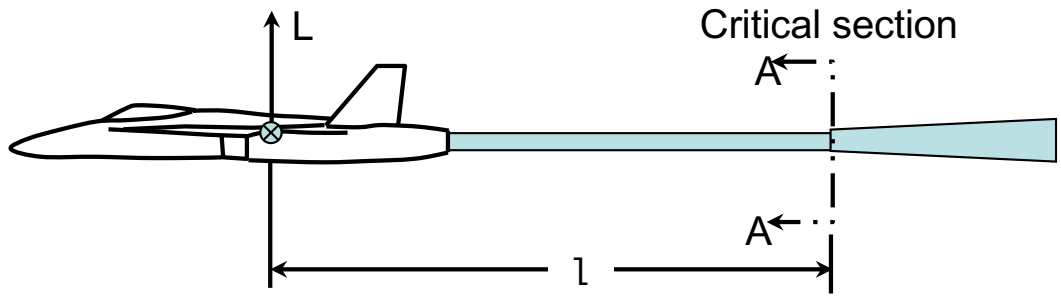
$$\text{Divergence criteria} \quad \frac{\Delta F_N}{\boldsymbol{\Delta\alpha}} \leq \frac{(0.4)\Delta P}{\Delta\theta}$$



$$\text{Slope} = \frac{\Delta P}{\boldsymbol{\Delta\theta}} \ \#/^\circ$$



STING DIVERGENCE - ANOTHER METHOD

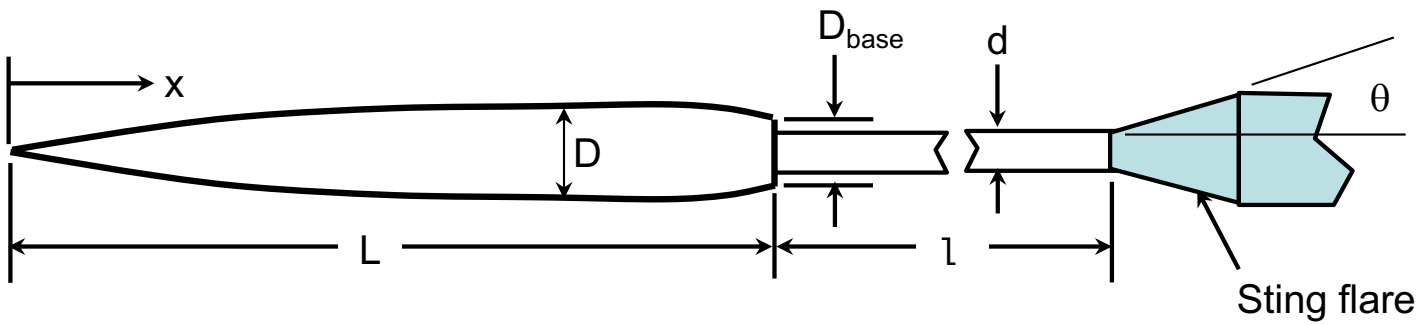


- **<u>Sting will diverge when</u>**
  - $d/L = dw/d\theta = 2EI_{xx} / l^2$
  - where
    - l length
    - L Lift
    - A angle of attack
    - E modulus of material
    - I_{xx} moment of inertia at critical section
  - now: $d/L = C_{L\alpha} (q/p_t) S_{ref} p_t$
  - where
    - $C_{L\alpha}$ lift curve slope in radians
    - q/p_t ratio of dynamic pressure to stagnation pressure
    - $S_{ref} p_t$ is the product of reference area and stagnation pressure
  - Therefore: For sting divergence

$$p_t = (2EI_{xx} / l^2)\{1/[C_{L\alpha} (q/p_t) S_{ref} p_t]\}$$

  - For safe practice it is recommended that p_t for sting divergence be at least twice the test p_t

STING INTERFERENCE

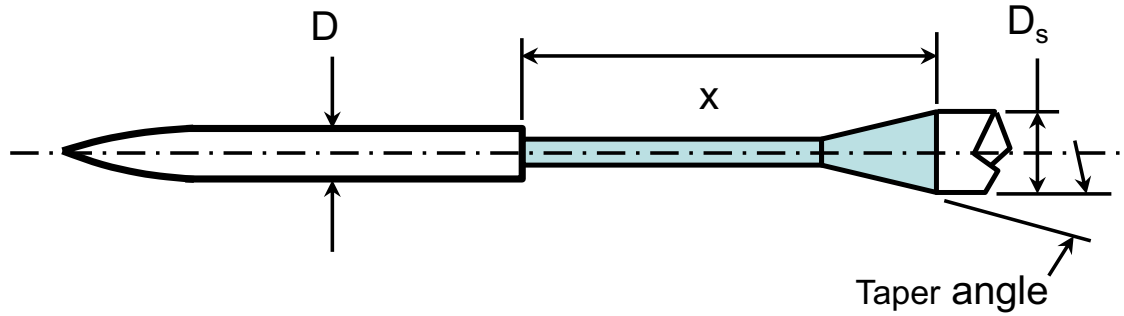


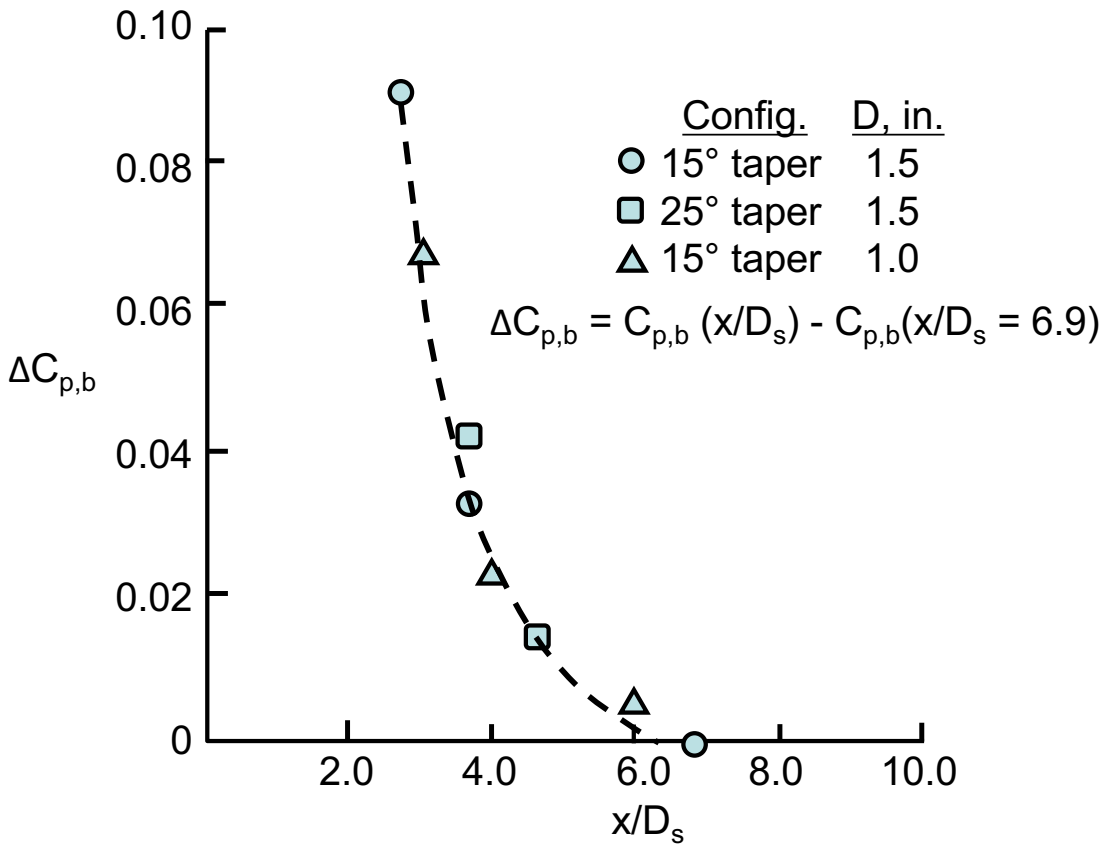
- <u>Factors Affecting Sting Interference</u>
  - d/D_{base} Ratio of sting diameter to base diameter
  - l/D_{base} Length of cylindrical portion of sting
  - θ Sting flare (taper) angle

- <u>Sting Interference "Rules of Thumb"</u>
  - With $\theta = 8°$, l/D_{base} should be ≥ 4 if $M \geq 1$
  - For large θ, l/D_{base} must increase
  - For $d/D_{base} \leq 0.9$ there are only small effects on "forebody (boattail) drag" (large effects on base drag) $C_{D,F} = C_{D,total} - C_{D,base}$

OTHER STING DESIGN CONSIDERATIONS

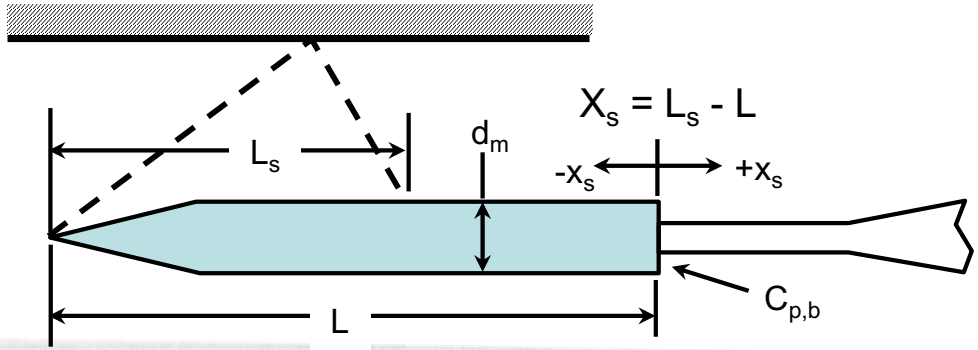
STING LOCATION EFFECTS ON BASE PRESSURE COEFFICIENT (M = 0.9)

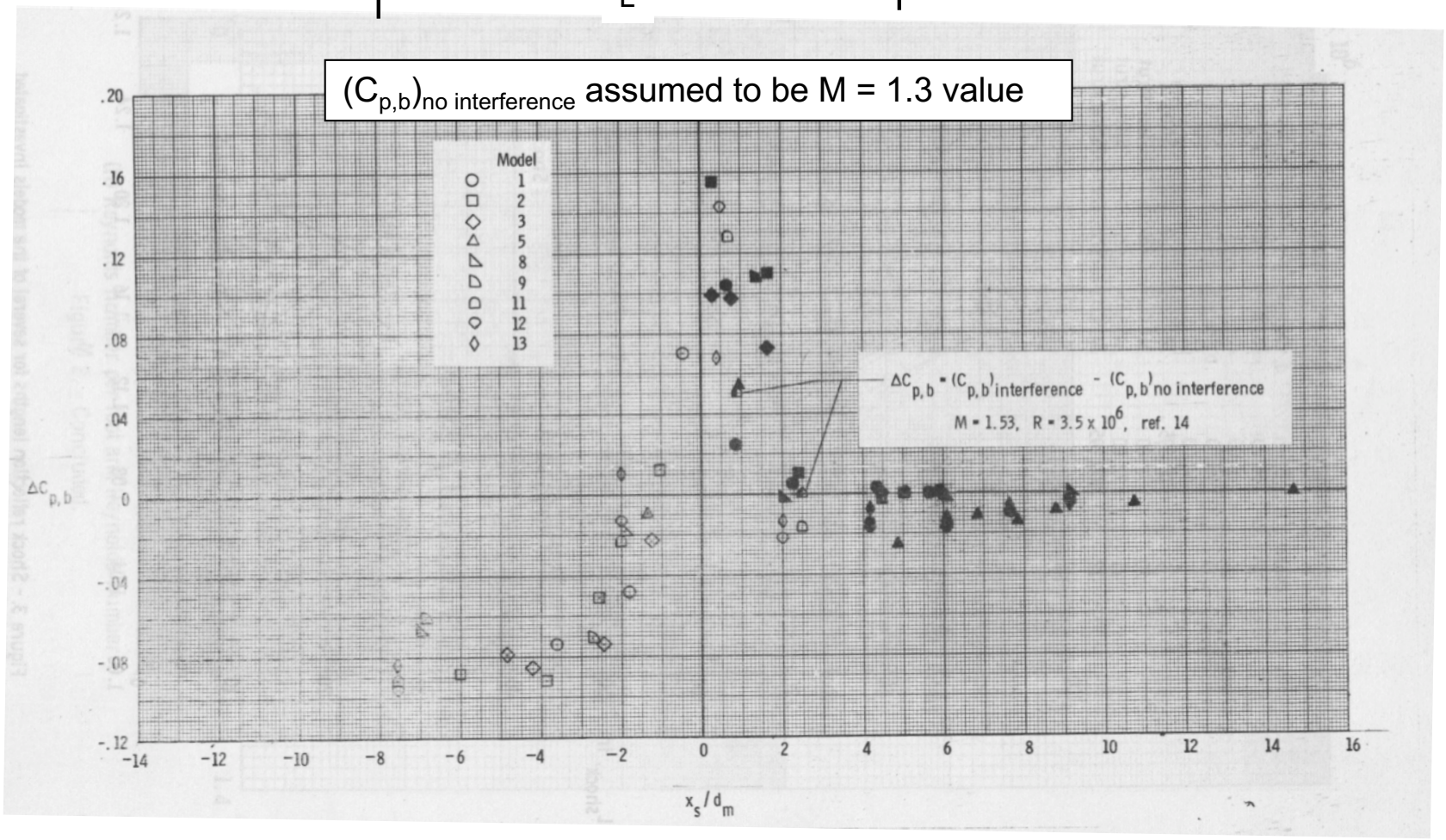




OTHER STING DESIGN CONSIDERATIONS

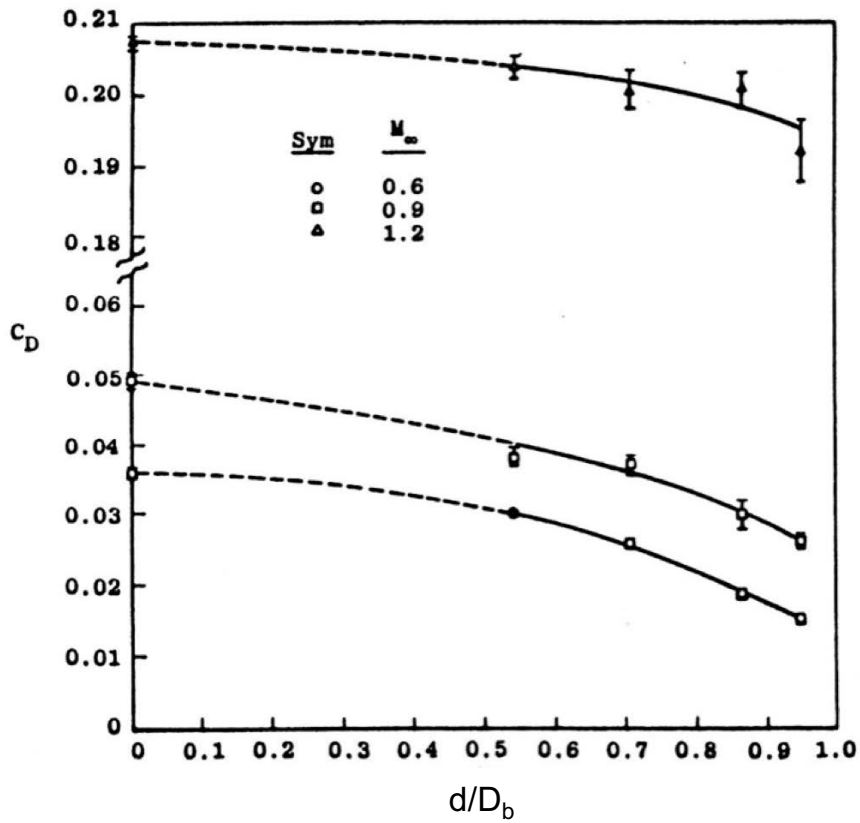
REFLECTED SHOCK LOCATION EFFECTS ON BASE PRESSURE



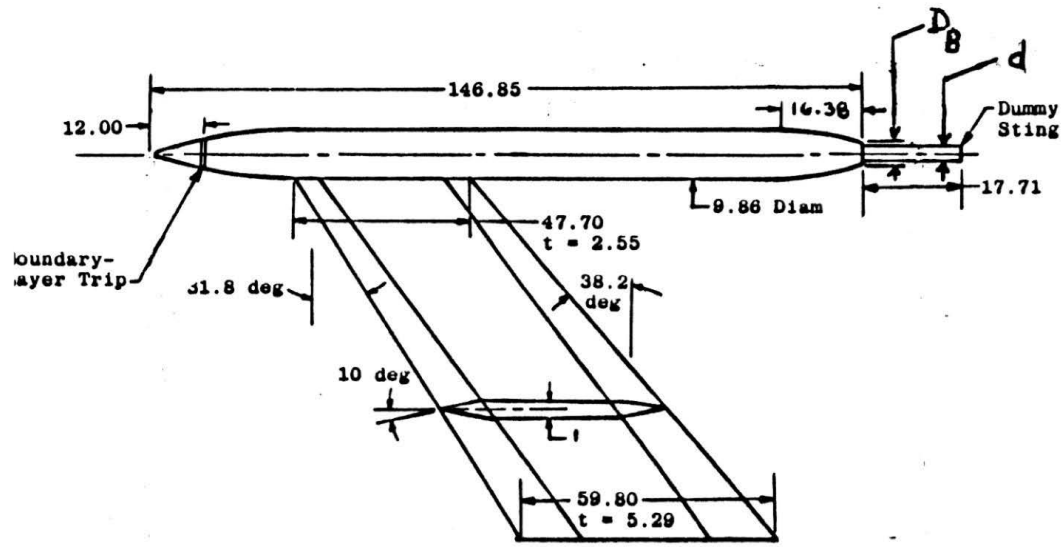


OTHER STING DESIGN CONSIDERATIONS

STING-TO-BASE DIAMETER EFECTS ON AFTERBODY DRAG COEFFICIENT



Variation of jet-off afterbody drag with sting size



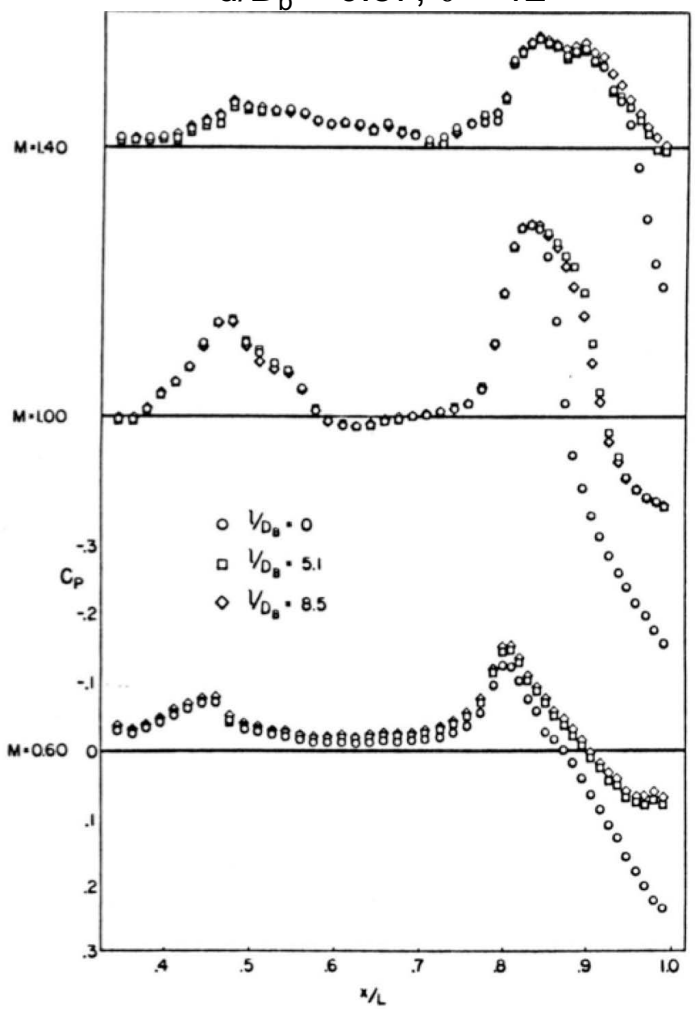
Reference: AEDC TR-80-8

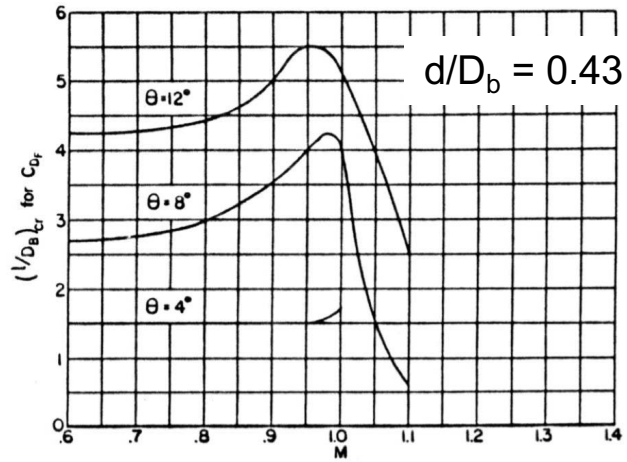
C_D based on body cross-sectional area

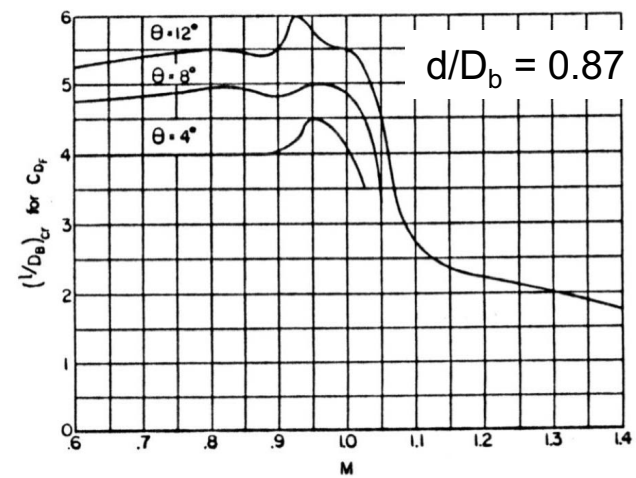
OTHER STING DESIGN CONSIDERATIONS

MODEL BOATTAIL $C_{p,s}$ AND CRITICAL STING LENGTH RATIOS

$d/D_b = 0.87$, $\theta = 12°$



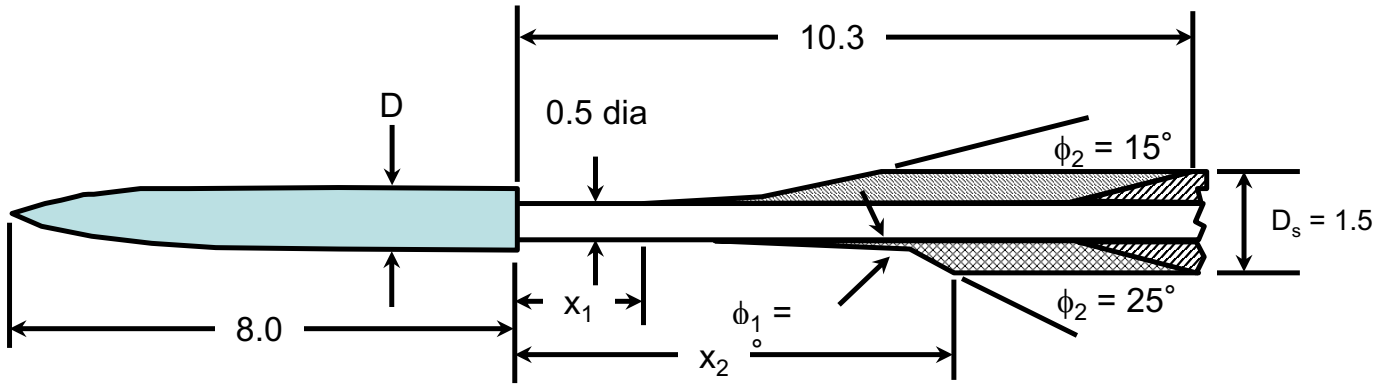


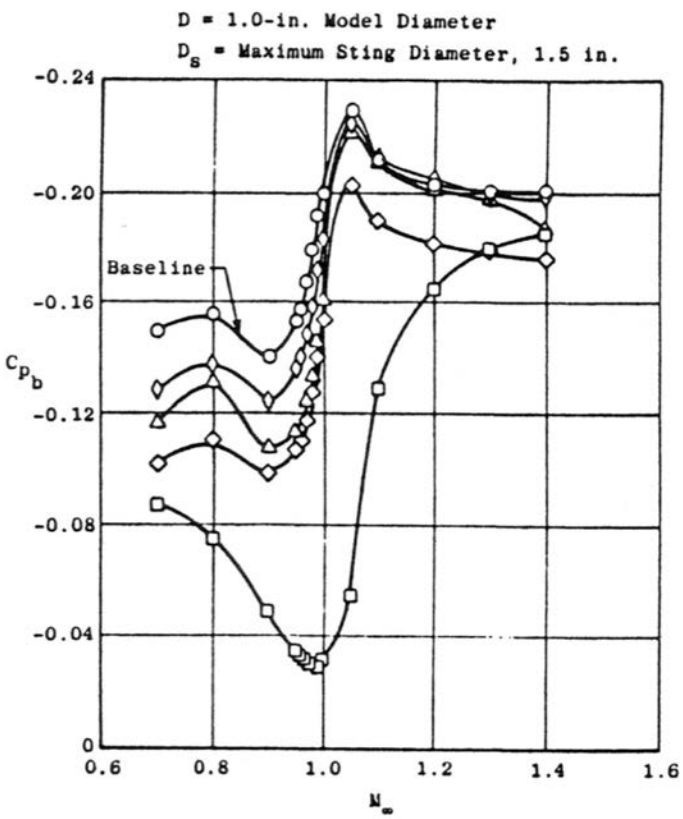


Reference: RM A57I09

OTHER STING DESIGN CONSIDERATIONS

MODEL BASE PRESSURE COEFFICIENTS FOR VARIOUS STING CONFIGURATIONS

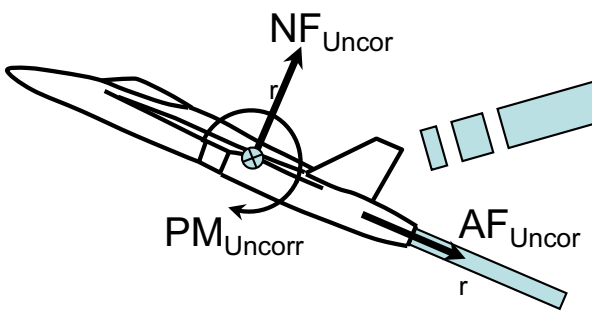




	x_1/D	x_2/D	x_2/D_s	ϕ_1, deg	ϕ_2, deg
○	8.4	10.3	6.9	0	15
□	0.5	4.0	2.7	2.0	15
△	2.0	5.5	3.7	2.0	15
◇	0.5	5.5	3.7	2.0	25
◊	2.0	7.0	4.7	2.0	25

Reference: AEDC TR-80-8

A REFRESHER ON WHAT YOU SHOULD ALREADY KNOW



Raw Balance Readings

↓

Apply Balance Interactions
Using Initial Tare Loads

↓

Apply Attitude Tares

↓

Determine α and β
(Apply tunnel angularity corrections)

←

Body Axis Components
Rotation & Translation
Balance to Model Axis

↓

Apply corrections for:
Base Pressure
Nacelle Internal Forces & Moments
Buoyancy

↓

Determine Coefficients About:
Body Axis
Stability Axis
Wind Axis
Alternate Axis

INITIAL MODEL WEIGHT AND ATTITUDE TARES

DEFINITIONS

- **INITIAL WEIGHT TARES**: Forces and moments exerted on balance due to weight of the model when balance is is at attitude for recording wind-off data zeros
  - Used only in calculation of balance interactions

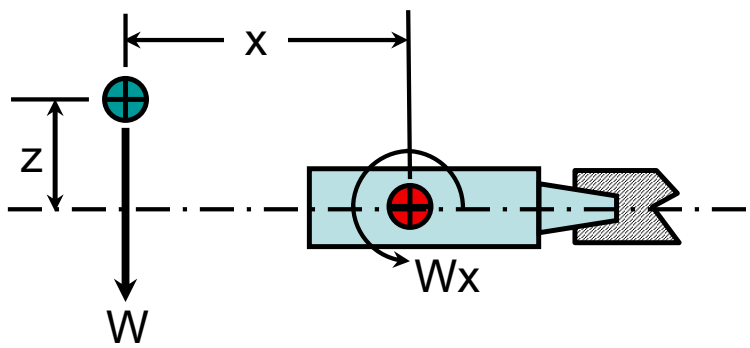
- **ATTITUDE TARES**: The changes in forces and moments felt by the balance due to model weight as model (and balance) attitude is changed relative to the wind-off attitude
  - Each data point must be corrected for attitude tares to obtain the appropriate aerodynamic data

MODEL WEIGHT RELATED IN SIMPLIFIED TERMS

Initial Weight Tares

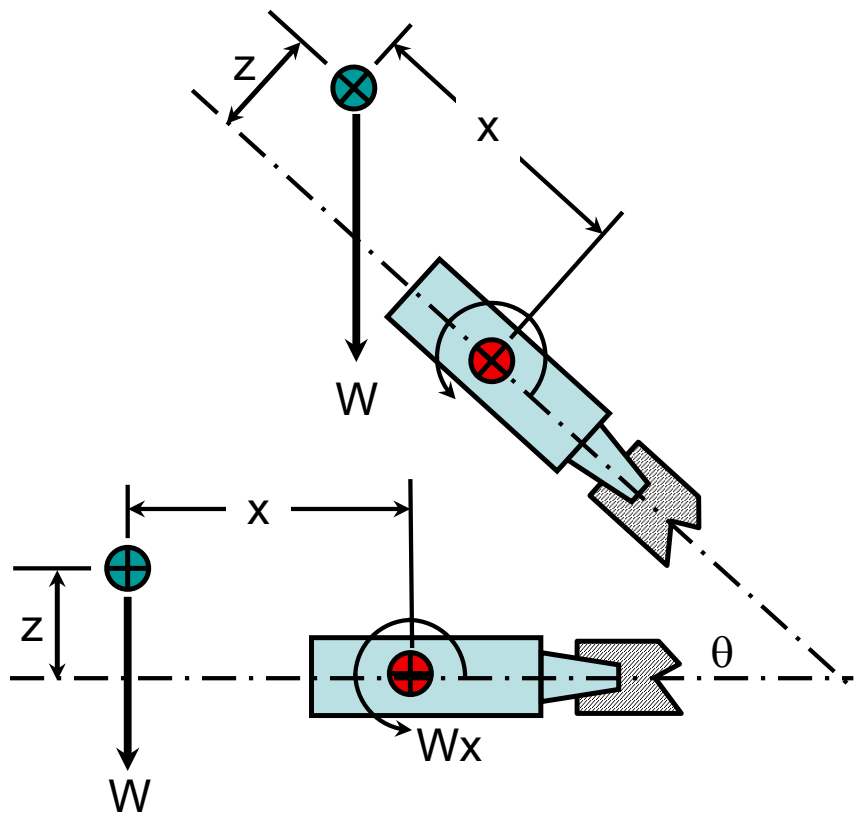
An interaction matrix relative to the unloaded (bare) balance condition Is obtained from the balance calibration. Then, in use, the balance is treated as a differential force and moment transducer.

For $\theta_0 = 0°$



NF0(I) = -W
AF0(I) = 0
PM0(I) = -Wx

Attitude Tares



AFTARE = W(sin θ- sinθ_0)
NFTARE = -W(cos θ - cosθ_0)
PMTARE = AFTARE(z) + NFTARE(x)

DETERMINATION OF MODEL INITIAL WEIGHT AND ATTITUDE TARES

To Calculate the Initial Weight Tares and Attitude Tares the Following Must Be Determined:

1. The weight (W) of the model.

2. The location of the model reference center of gravity relative to the balance moment reference. (x, y, z).

This Can Be Done By:

1. Use of scales, etc to weigh the model and to determine the center of gravity location prior to the wind tunnel test.

2. Use the balance and attitude variation in the tunnel to “weigh” the model (the easiest and most common approach)

IN-TUNNEL DETERMINATION OF MODEL WEIGHT AND ATTITUDE TARES

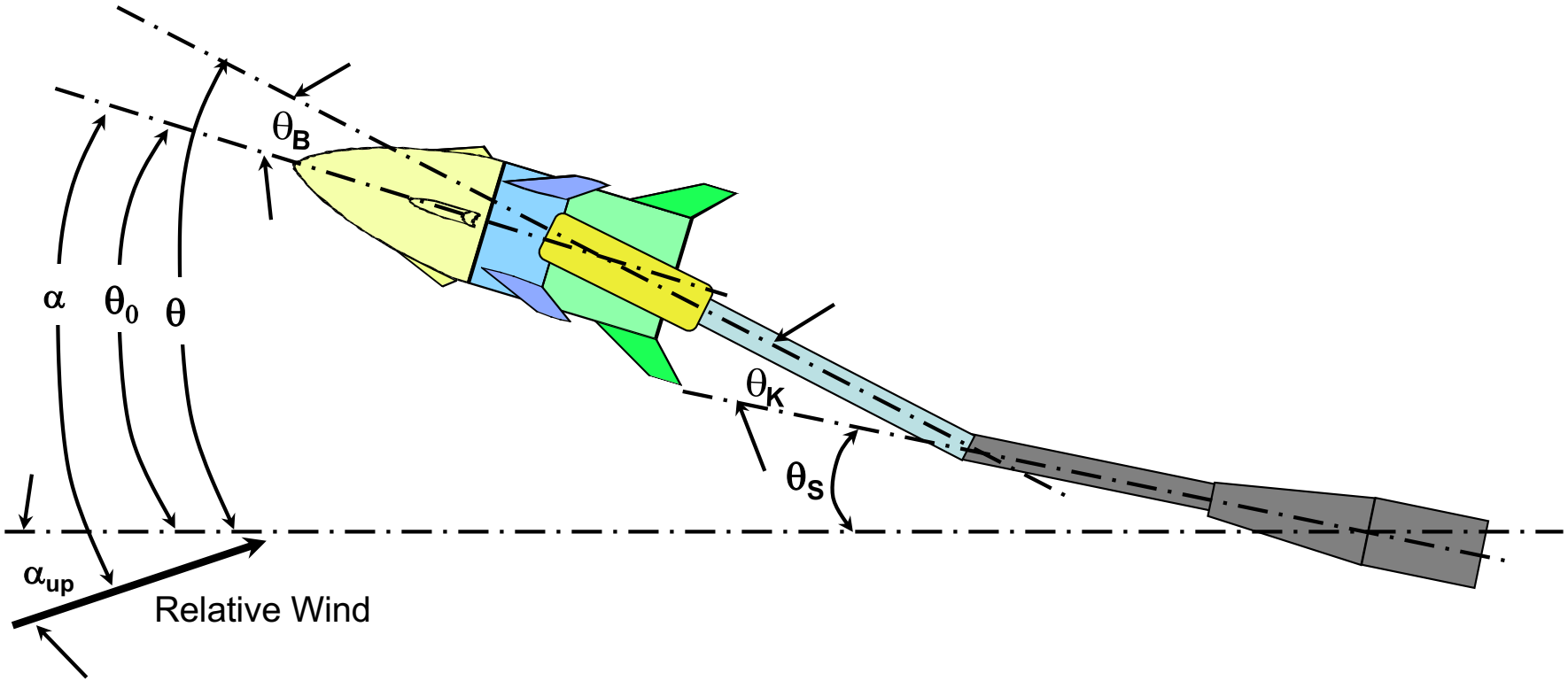
- METHOD 1: Pitch model through maximum possible of support mechanism angle recording data at discrete angles. The data system then recognizes a run code and automatically uses AF output to calculate model weight. Appropriate moment outputs (depending on model roll) are used to determine moment tares and x, y, and z.

- METHOD 2: Roll model through 270° using strut roll mechanism recording data at each 90° roll increment. The data system then uses NF and SF output to determine weight. PM or YM output are used to determine pitch (or yaw). RM output is used to determine roll tare.

- The results of either method should be examined critically before proceeding to the test runs since unique circumstances exist that can produce bizarre results (c.g. 24 inches from the model base) when balance resolution is too small or the distance between the balance moment reference center and the model c.g. are very small. Results of either method or the two methods combined provide a complete set of initial weight and attitude tares that are automatically input for subsequent tunnel runs.

MODEL ATTITUDE

ATTITUDE DETERMINATION NOT SO SIMPLE



θ_S	Strut or support system pitch angle
θ_K	Euler pitch angle to account for knuckle or offset sting
θ_0	Wind off attitude of balance
θ_B	Euler pitch rotation between balance and model reference axis
θ	Model Euler pitch angle
α_{up}	upflow angle
α	Model angle of attack

DETERMINE MODEL ATTITUDE IN TUNNEL
THEORY AND BACKGROUND

To reduce wind tunnel aerodynamic data to coefficient form, it is necessary to determine x, y, z components of various velocity vectors, force vectors, and moment vectors in any of the following axis systems:

Wind Axis

Stability Axis (not shown)

Gravity Axis

Balance Axis

Body Axis

Missile Axis (not shown)

DETERMINE MODEL ATTITUDE IN TUNNEL
USE EULER ANGLE THEORY

- Use of Euler angle theory to rotate to axis systems

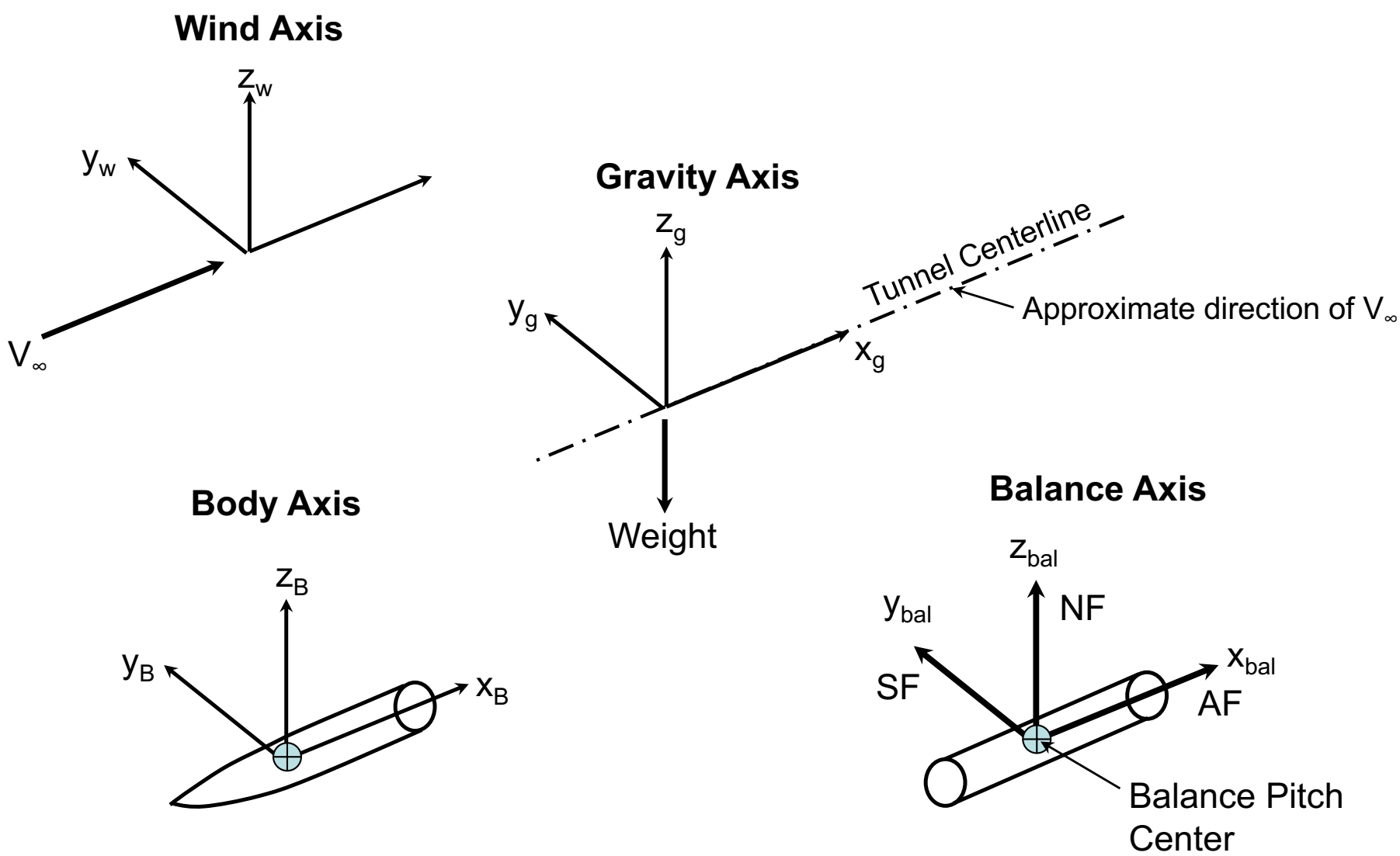
- The components of a vector in one axis system are rotated to other axes systems for some data reduction systems.

- That is
  - Any axis system can be aligned with any other axis system by a translation and three rotations, providing that the rotations are a yaw, pitch, and roll.

  - Any series of consecutive rotations are equivalent to some yaw, pitch, roll rotation.

  - The resulting rotation matrix is orthogonal

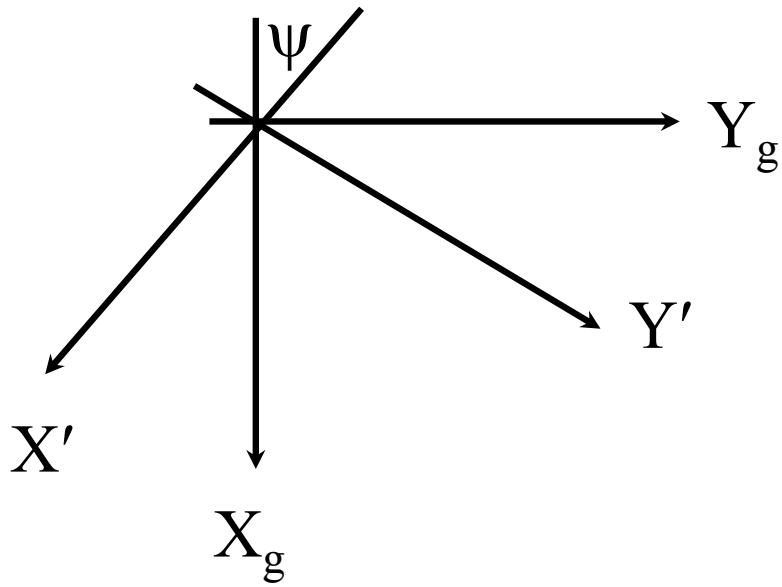
DETERMINE MODEL ATTITUDE IN TUNNEL
AXES DIFINITIONS



ROTATION OF FORCES

GRAVITY AXIS SYSTEM TO BALANCE AXIS SYSTEM

First Rotation - Yaw



$$X' = X_g \cos\psi - Y_g \sin\psi$$
$$Y' = X_g \sin\psi + Y_g \cos\psi$$
$$Z' = Z_g$$

or

$$\begin{vmatrix} X' \\ Y' \\ Z' \end{vmatrix} = \begin{vmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} X_g \\ Y_g \\ Z \end{vmatrix}$$

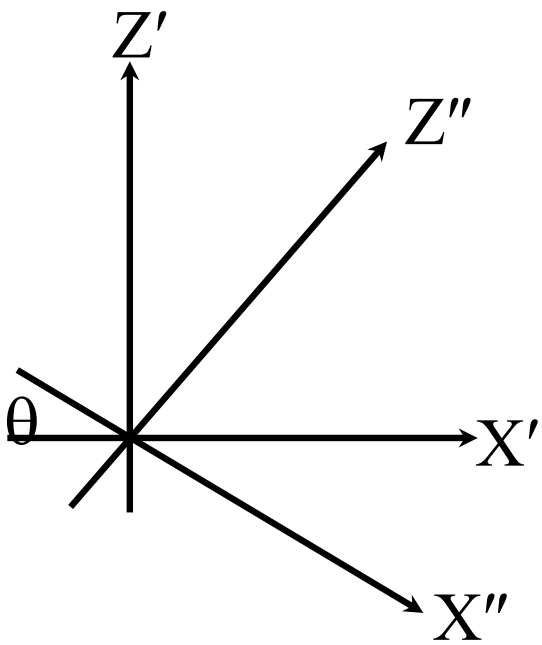
or

$$F' = T_\psi F_g$$

ROTATION OF FORCES - Cont.

GRAVITY AXIS SYSTEM TO BALANCE AXIS SYSTEM

Second Rotation - Pitch



$$X'' = X'\cos\theta - Z'\sin\theta$$
$$Y'' = Y'$$
$$Z'' = X'\sin\theta + Z'\cos\theta$$

or

$$\begin{vmatrix} X'' \\ Y'' \\ Z'' \end{vmatrix} = \begin{vmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{vmatrix} \begin{vmatrix} X' \\ Y' \\ Z' \end{vmatrix}$$

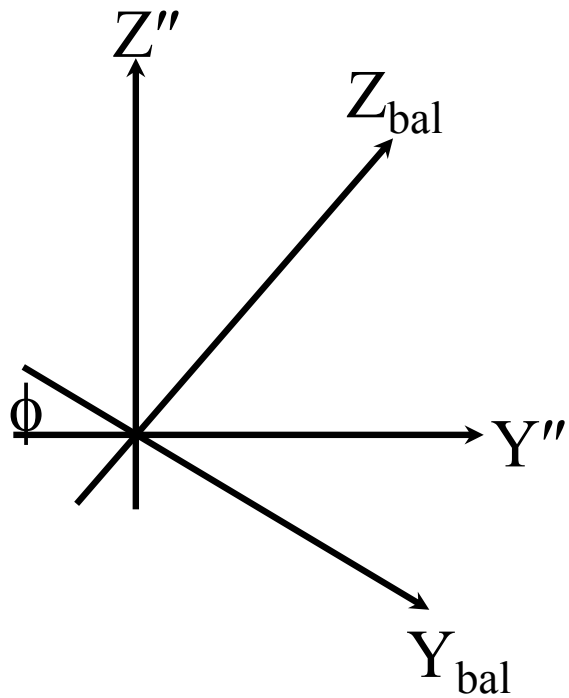
or

$$F'' = T_\theta F'$$

ROTATION OF FORCES - Cont.

GRAVITY AXIS SYSTEM TO BALANCE AXIS SYSTEM

Third Rotation - Roll



$$X_{bal} = X''$$
$$Y_{bal} = Y''\cos\phi - Z''\sin\phi$$
$$Z_{bal} = Y''\sin\phi + Z''\cos\phi$$

or

$$\begin{vmatrix} X_{bal} \\ Y_{bal} \\ Z_{bal} \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{vmatrix} \begin{vmatrix} X'' \\ Y'' \\ Z'' \end{vmatrix}$$

or

$$F_{bal} = T_{\phi} F''$$

COMBINED ROTATION OF FORCES

GRAVITY AXIS SYSTEM TO BALANCE AXIS SYSTEM

$$F_{bal} = T_{\phi} F''$$
$$F_{bal} = T_{\phi}(T_{\theta} F')$$
$$F_{bal} = T_{\phi} T_{\theta}(T_{\psi} F_g)$$

Therefore:

$$\begin{vmatrix} F_x \\ F_y \\ F_z \end{vmatrix}_{bal} = \underbrace{\begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{vmatrix}}_{\text{(Roll)}} \underbrace{\begin{vmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{vmatrix}}_{\text{(Pitch)}} \underbrace{\begin{vmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{vmatrix}}_{\text{(Yaw)}} \begin{vmatrix} F_x \\ F_y \\ F_z \end{vmatrix}_g$$

COMBINED ROTATION OF FORCES

GRAVITY AXIX SYSTEM TO BALANCE AXIS SYSTEM - Cont.

Now:

$$\begin{vmatrix} F_x \\ F_y \\ F_z \end{vmatrix}_g = \begin{vmatrix} 0 \\ 0 \\ -W \end{vmatrix}$$

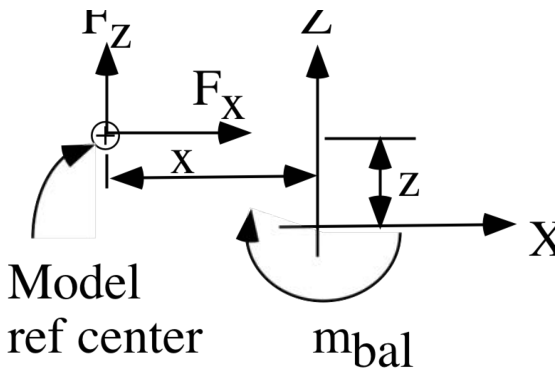
Substituting and performing the matrix multiplication gives:

$$\begin{vmatrix} F_x \\ F_y \\ F_z \end{vmatrix}_{bal} = \begin{vmatrix} \cos\theta\cos\psi & -\sin\psi\cos\theta & -\sin\theta \\ -\sin\phi\sin\theta\cos\psi+\cos\phi\sin\psi & \sin\phi\sin\theta\sin\psi+\cos\phi\cos\psi & -\sin\phi\cos\theta \\ \cos\phi\sin\theta\cos\psi+\sin\phi\sin\psi & -\cos\phi\sin\theta\sin\psi+\sin\phi\cos\psi & \cos\phi\cos\theta \end{vmatrix} \begin{vmatrix} 0 \\ 0 \\ -W \end{vmatrix}$$

Therefore:

$$F_{x,bal} = W\sin\theta$$
$$F_{y,bal} = W\sin\phi\cos\theta$$
$$F_{z,bal} = -W\cos\phi\cos\theta$$

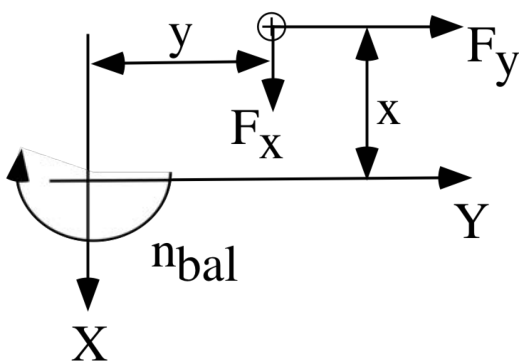
CALCULATION OF MOMENTS PRODUCED BY MODEL WEIGHT VECTOR IN BALANCE AXIS SYSTEM



Pitch:

$m_{bal} = xF_z + zF_x$

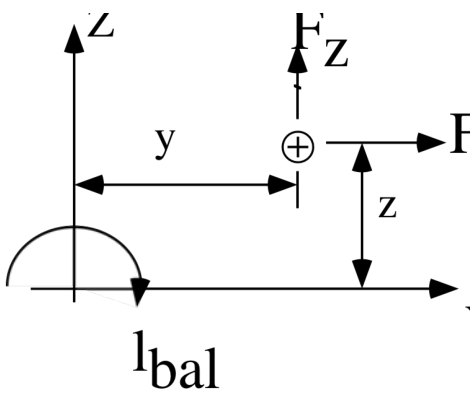
$m_{bal} = -Wx\cos\phi\cos\theta + Wz\sin\theta$



Yaw:

$n_{bal} = xF_y + yF_x$

$n_{bal} = Wx\sin\phi\cos\theta + Wy\sin\theta$



Roll:

$l_{bal} = -yF_z + zF_y$

$l_{bal} = Wy\cos\phi\cos\theta + Wz\sin\phi\cos\theta$

TARE COMPONENTS OF THE MODEL WEIGHT VECTOR IN THE BALANCE AXIS SYSTEM

<u>To Summarize</u>

The tare components of the model weight vector in the balance axis system are:

$$AF = F_{x,bal} = W\sin\theta$$

$$SF = F_{y,bal} = W\sin\phi\cos\theta$$

$$NF = F_{z,bal} = -W\cos\phi\cos\theta$$

$$PM = m_{bal} = -Wx\cos\phi\cos\theta + Wz\sin\theta$$

$$YM = n_{bal} = Wx\sin\phi\cos\theta + Wy\sin\theta$$

$$RM = l_{bal} = Wy\cos\phi\cos\theta + Wz\sin\phi\cos\theta$$

Now:The initial weight tares for the model/balance are computed using the above equations and the values of θ and ϕ at data zero (θ_0 and ϕ_0)

CALCULATION OF ATTITUDE TARES

$$\Delta F_{bal} = F_{bal} - F_{bal,0}$$

Therefore:

$$\Delta AF = F_{x,bal} = W(\sin\theta - \sin\theta_0)$$

$$\Delta SF = F_{y,bal} = W(\sin\phi\cos\theta - \sin\phi_0\cos\theta_0)$$

$$\Delta NF = F_{z,bal} = -W(\cos\phi\cos\theta - \cos\phi_0\cos\theta_0)$$

$$\Delta PM = m_{bal} = -Wx(\cos\phi\cos\theta - \cos\phi_0\cos\theta_0) + Wz(\sin\theta - \sin\theta_0)$$

$$\Delta YM = n_{bal} = Wx(\sin\phi\cos\theta - \sin\phi_0\cos\theta_0) + Wy(\sin\theta - \sin\theta_0)$$

$$\Delta RM = l_{bal} = Wy(\cos\phi\cos\theta - \cos\phi_0\cos\theta_0) + Wz(\sin\phi\cos\theta - \sin\phi_0\cos\theta_0)$$

DETERMINE MODEL ATTITUDE IN TUNNEL
AXES ROTATIONS

- <u>Rotation From Wind to Gravity Axes</u>
  - Following order will always be used:
    1. ψ_u sideflow
    2. θ_u upflow

- <u>Rotation From Gravity to Balance Axes</u>
  - Following order should be used** (Note: Start at support strut and work forward)
    1. θ_s strut pitch angle
    2. φ_k strut roll angle
    3. ψ_k yaw knuckle
    4. θ_k pitch knuckle

    Order dependent on installation

    5. θ_d pitch deflection
    6. ψ_d yaw deflection
    7. φ_d roll deflection

    Order not important since these angles are small*

*For sweep tests, θ_d should be first, for b sweep tests ψ_d should be first, however

**A notable exception to the order given is when “angle of attack” indicators in model are used

DETERMINE MODEL ATTITUDE IN TUNNEL
AXES ROTATIONS - Cont

- <u>Rotation From Balance to Body Axes</u>
  - Following angles will be used in order necessary:
    - θ_B pitch
    - φ_B roll
    - ψ_B yaw
- Rotation From Gravity to Balance Is Required for Weight Tare Calculations
- Rotation From Wind to Body Is Required to Determine α and β

DETERMINE MODEL ATTITUDE IN TUNNEL

CALCULATION OF α AND β

$$\alpha = \tan^{-1}(w/u) \qquad \text{and} \qquad \beta = \sin^{-1}(v/V_\infty)$$

Where u, v, w are x, y, z components of V_∞ in body axis system. Therefore, a rotation from wind axis system to body axis system is required.

FLOW ANGULARITY DETERMINATION

1. Starts long before the test by making sure the model can be leveled precisely upright and inverted whenever necessary during the test. (Provision should be made for leveling when the model is at ±90° for tests requiring sideslip testing). Make leveling fixture identical weight to any model component removed to accept fixture.

2. Level model inverted and run a baseline configuration at θ= -2° to 2° at 0.25° increments at all Mach numbers of test plan. If radically different spanned lifting surfaces are to be tested later, they should also be tested inverted (e.g., variable sweep wings).

3. Level model upright and run baseline configuration at all planned Mach numbers including the same -2° to 2° increments. (This need not be a partial run.)

4. Compute model data for φ = 0° (upright run) and φ = 180° (inverted run).

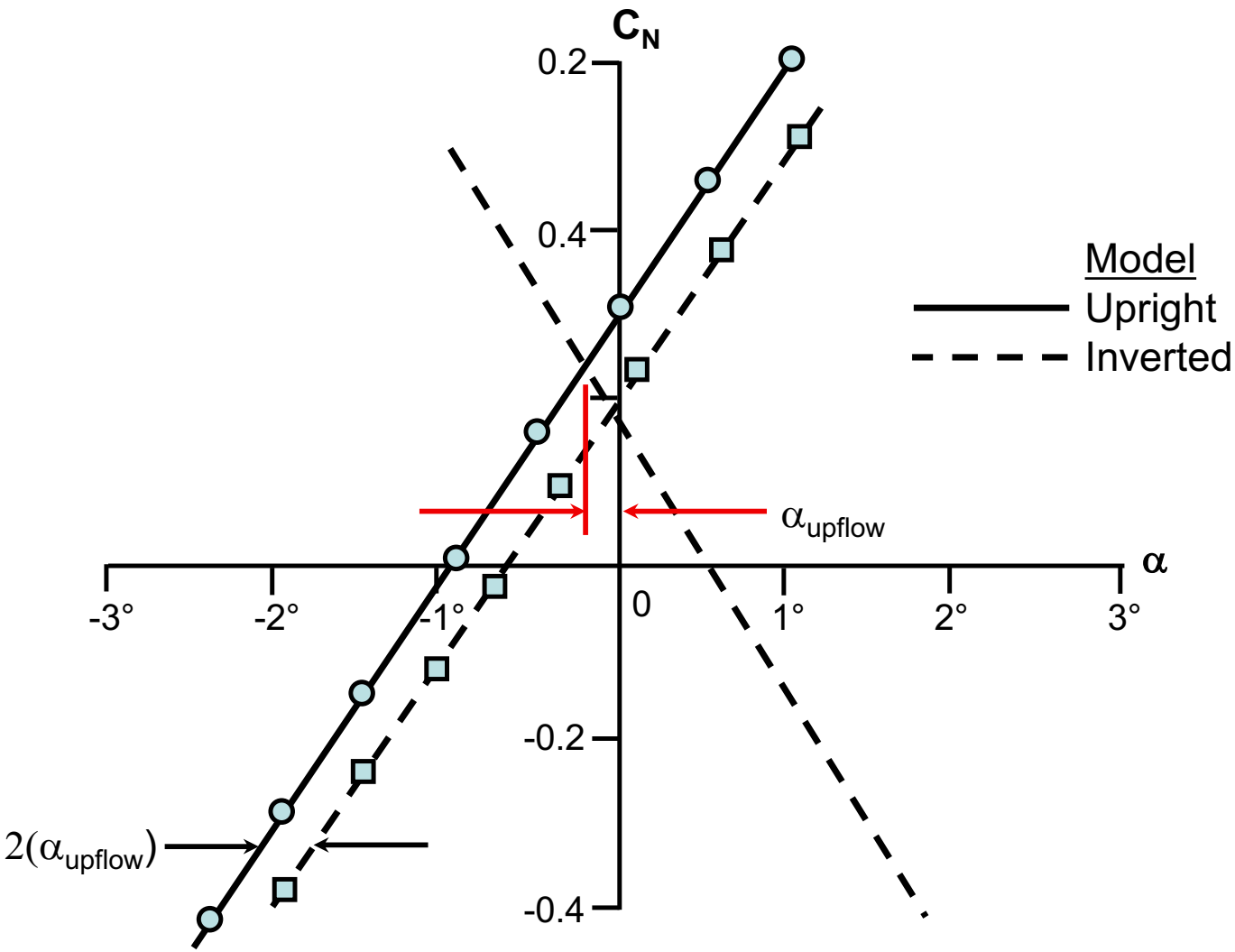
5. Plot C_N vs α for upright configuration and C_N vs -α for inverted run at each Mach number.

6. Prepare upflow table for inclusion in the data reduction program.

7. Recompute upright and inverted data with the upflow correction included to verify that the C_N vs σ data collapse to a single curve at values of α near 0°.

8. If sideslip testing is included in the test plan, the flow angularity determination is more complicated. An empirical interpolation capability has been determined so that flow flow angularity in two planes can be estimated at various combinations of model θ and φ once θ_u and ψ_u have been determined.

DETERMINATION OF UPFLOW ANGLE



UPFLOW ANGLE DETERMINATION FOR β SWEEP TESTS AT FIXED α

1. Make run with model rolled +90°.

2. Make run with model rolled -90°.

3. Make analysis similar to that required for a sweep tests. However, plot C_Y as a function of yaw angle ψ. (note that $\psi = -\beta$).

4. θ_u is angle correction requide to collapse C_Y vs $(-\beta)$ ψ data to one curve.

METHODS FOR DETERMINING SIDEFLOW

- <u>For Alpha Sweep Tests at Fixed Yaw</u>:
  - Determine variation of C_Y with yaw (ψ) (i.e., $C_{Y\psi}$)
  - Using data obtained at $\alpha = 0°$ and relevant offset yaw angle solve the following equation for ψ_u:

$$\psi_u = \frac{C_Y\ (\text{at } \psi_{uncorrected*},\ \alpha = 0°)}{C_{Y\psi}} - \psi_{uncorrected*}$$

(That is, determine adjustment necessary to make $C_Y = 0$ at $\psi = 0°$)

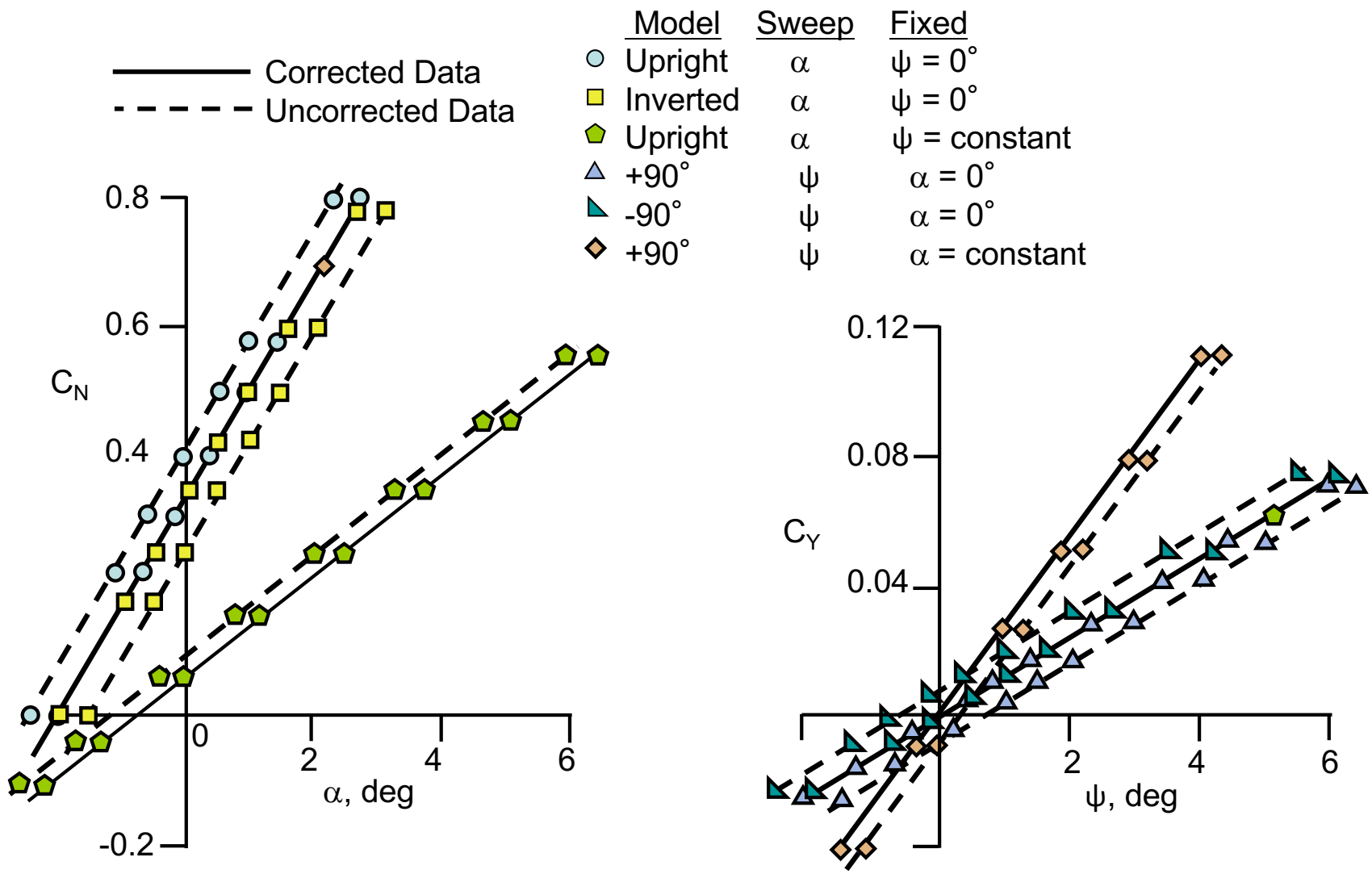
- <u>For Beta Sweep Tests at Fixed Alpha</u>:
  - Determine $C_{N\alpha}$ and C_N, $\alpha = 0°$.
  - Using data obtained at y = 0° (that is, model rolled ±90°) and relevant offset yaw angle solve the following equation for ψ_u:

$$\psi_u = \left(\frac{C_N\ (\text{at } \alpha_{uncorrected*},\ \beta = 0°)\ - C_N,\ \alpha = 0°}{C_{N\alpha}} \right) - \alpha_{uncorrected*}$$

Note: “Uncorrected” here means not corrected for sideflow

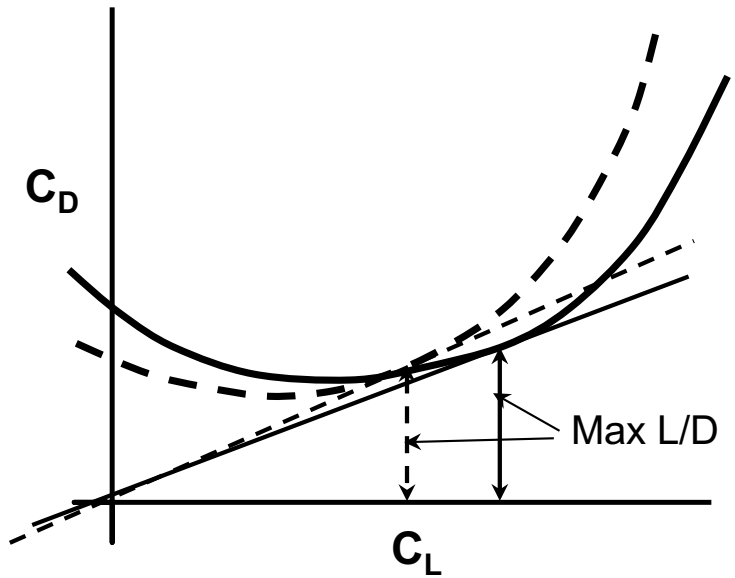
TO VERIFY SIDEFLOW ANGULARITY

1. Reprocess data with flow angularity corrections applied.
2. Plot corrected data to confirm results (See below)



IMPORTANCE OF α MEASUREMENTS

$$\text{Range} = 376\left(\frac{\eta}{c}\right)\left(\frac{C_L}{C_D}\right)\log_e\left(\frac{w_o}{w_1}\right)$$



- For
  - C-5A, 0.0001 error in C_D was equivalent to 1,000 lbs payload
  - HSR vehicle, 0.0001 error in C_D was equivalent to 10,000 lbs TOGW
  - F-14, error in α of 0.18° resulted in a loss of 200 miles in combat radius or 20% of the 500 mile requirement

OTHER CORRECTIONS/ADJUSTMENTS

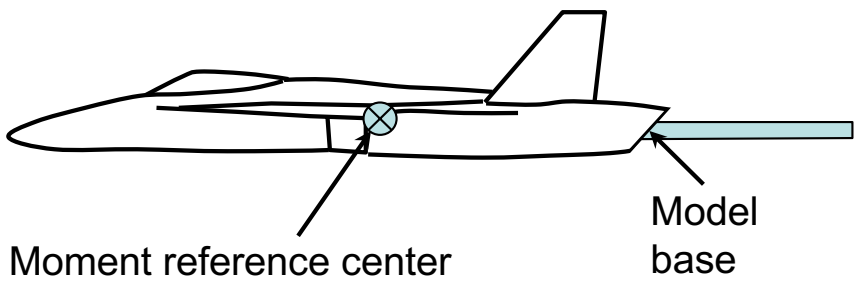
BASE PRESSURE

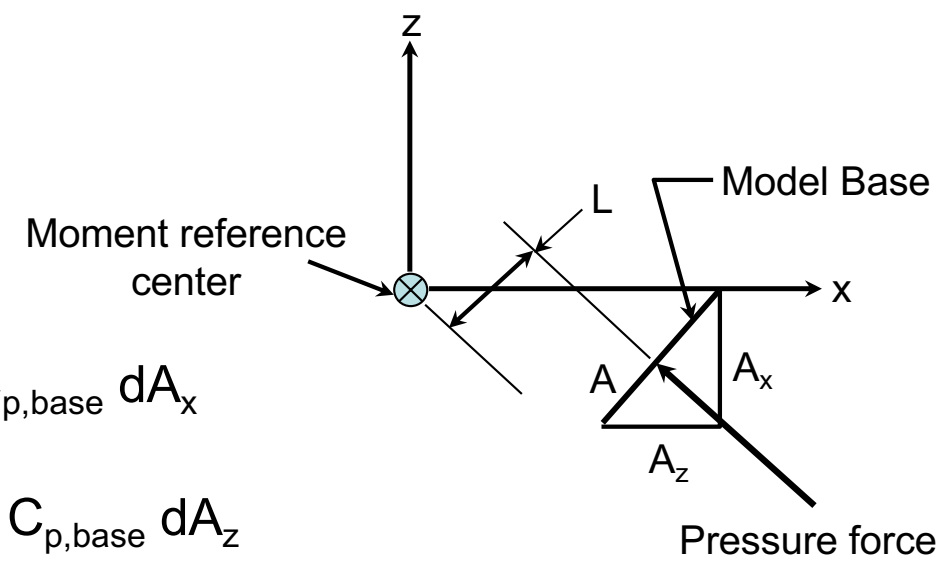
DUCT INTERNAL DRAG

BASE PRESSURE

BASE PRESSURE CORRECTIONS

PURPOSE: To adjust balance measurements for pressure tare force acting on model base. This tare force results from model/installation requirements for model support and is usually not representative of the pressure conditions existing at the base of a real airplane. Therefore, as a matter of convention the measured balance forces and moments are routinely adjusted to represent the condition of free-stream static pressure existing at the model base. Knowing that this adjustment has been made to the model data, it can be adjusted to the airplane base configuration if separate tests have been made to determine the incremental effects of sting interference and afterbody closure.





$$C_{A,base} = -\int C_{p,base}\, dA_x$$

$$C_{N,base} = +\int C_{p,base}\, dA_z$$

$$C_{m,base} = +\int C_{p,base}\, L dA$$

BASE PRESSURE CORRECTIONS-Cont.

$$C_{A,c} = C_{A,measured} - C_{A,base}$$

$$C_{N,c} = C_{N,measured} - C_{N,base}$$

$$C_{m,c} = C_{m,measured} - C_{m,base}$$

Note: C_Y, C_n, C_l can also be corrected for base pressure in a similar way but it is generally not necessary since afterbody/installation modifications to the configuration are generally symmetric about the vertical plane.

The integration of pressures is usually done by assigning an area to each base pressure orifice and summing the products of the areas and pressures. On some models, there will be orifices in the physical base of the model as well as pressure tubes in the open area (often referred to as "sting cavity pressures") at the model base through which the sting passes. (It is not recommended that the base or cavity pressures be manifolded to reduce the number of pressure transducers required since this can lead to erroneous results. Also, open tubes in the sting cavity area are usually installed with the open area pointed downstream in case there is unexpected flow through the model.)

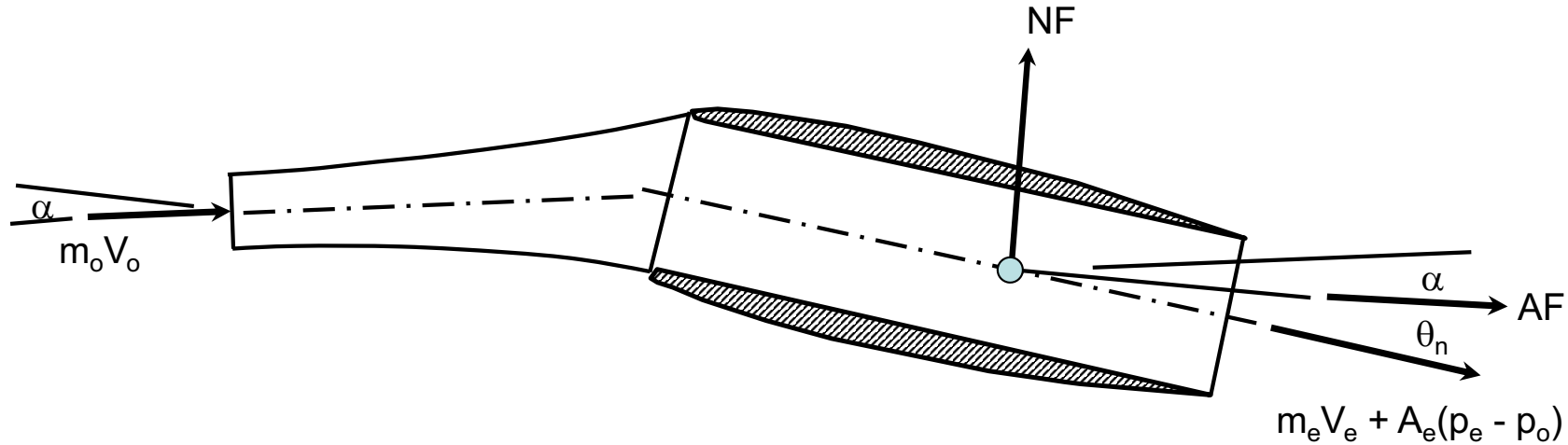
There is no way to make a base pressure correction if there is flow through the model.

$$F_x = \sum_{I=1}^{N} \left(C_{p,base}\right)_I \Delta A_I q_o S_{ref}$$

INTERNAL DUCT DRAG

INTERNAL DRAG CORRECTION

PURPOSE: To correct balance measurements for tare force due to skin friction and momentum losses inside the ducts of flow-through nacelles



$$\text{Net Axial Force} = [m_eV_e + A_e(p_e - p_o)]\cos\theta_n - m_oV_o\cos\alpha$$

$$\text{Net Normal Force} = m_oV_o\sin\alpha - [m_eV_e + A_e(p_e - p_o)]\sin\theta_n$$

Note: ram drag = m_oV_o

gross thrust = $m_eV_e + A_e(p_e - p_o)$

Corrections to the other balance measurements must also be made to account for any cant angle of the nacelles.

INTERNAL DRAG CORRECTION - Cont.

$$\text{Net Drag Force} = [m_e V_e + A_e(p_e - p_o)][\cos\theta_n \cos\alpha - \sin q_n \sin\alpha] - m_o V_o$$

For flow-through nacelles

$$m_o = m_e$$

and

$$V_o = M_o \sqrt{\gamma R T_o}$$

Therefore: To determine the internal drag, the following must be measured at the exit of the nacelle:

m_e -- Mass flow at exit

V_e -- Average flow velocity at exit

p_e -- Average static pressure at exit

INTERNAL DRAG CORRECTION - Cont.

In practice only total pressure profiles and static pressure profiles are actually measured since:

$$V_e = M_e\sqrt{\gamma R T_e} = \frac{M_e\sqrt{\gamma R T_e}}{\sqrt{1 + M_e^2}}$$

$$T_{T,e} = T_{T,o}$$

$$M_e = f(p_e/p_{t,e})$$

$$m_e = \rho_e V_e A_e = \sqrt{\gamma/R}\left(\frac{A_e M_e\sqrt{1 + M_e^2}}{\sqrt{T_{T,e}}}\right)$$

To make these measurements, a combination total/static pressure rake is used.

DUCT EXIT PRESSURE SURVEY RAKE NEEDS

1. The rake should be attached to the model to avoid displacement of the rake probes relative to the desired duct exit plane locations due to sting/balance deflections during testing.

2. Separate tunnel runs are required to obtained internal drag when duct exit plane pressure surveys are made.

3. Sufficient number of total pressure probes must be located close to the duct walls to adequately define boundary layer. However, care must be taken not to introduce blockage at the duct exit plane.

4. Static pressure should be measured by the rake orifices in the duct exit plane or on the duct wall at the exit if practical.

5. Care should be taken that the rake support structure be well aft of the duct exit plane and not be massive enough to project a pressure field forward to the duct exit plane. A duct static pressure tap can give some indication of this occurrence by comparing rake-on and rake-off readings.

6. Total and static pressure transducers should be sized and provided with the appropriate high quality reference pressure so that good resolution and accuracy is obtained for the rake local pressure measurements.

OTHER DETERMINATIONS OF INTERNAL DRAG

- Static Calibration Facility (Test facility with flow and force measuring systems)
  - Induce duct flow by reducing back pressure (high pressure air supply required)
  - Bell-mouth design and fabrication may be required for static test to avoid flow separation at inlet lip
  - Accurate metering of duct flow required
  - Accurate force measuring system required
  - Duct wall (near exit) pressures recorded as correlation parameter for use during wind tunnel testing
  - Boeing has an excellent calibration facility (high costs associated with facility)

- Analytic Computation Methods:
  - May be acceptable for some simple duct geometries
  - May require duct wall static pressure measurements near duct exit
  - Used during HSR testing. However, computational method only computed skin friction losses and did not include momentum losses

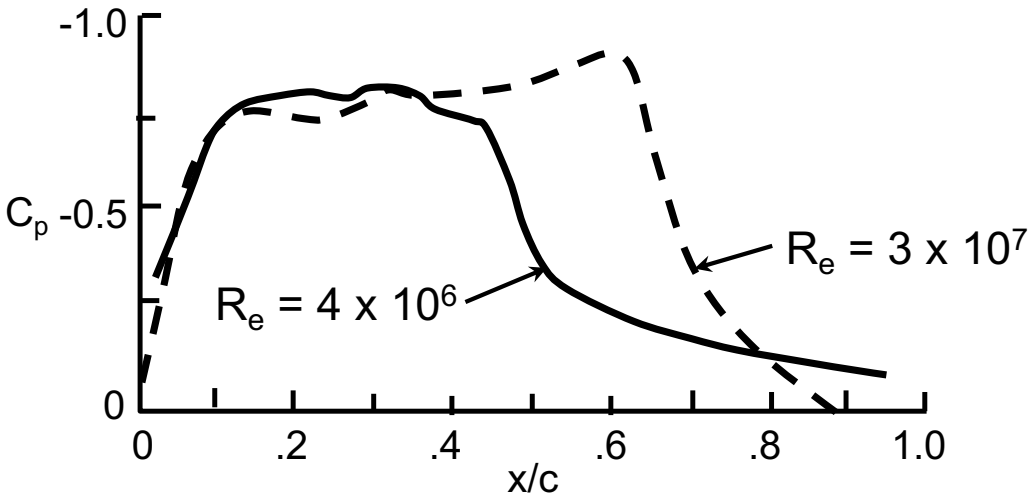
BOUNDARY LAYER TRANSITION

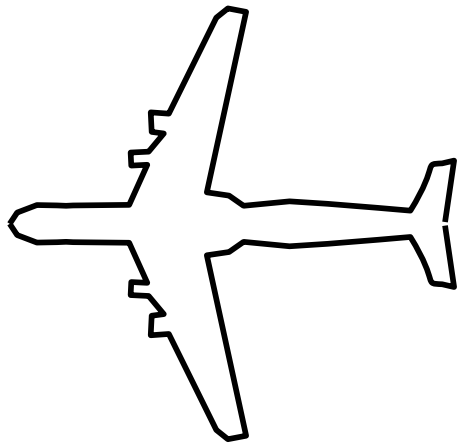
BOUNDARY LAYER TRANSITION FIXING

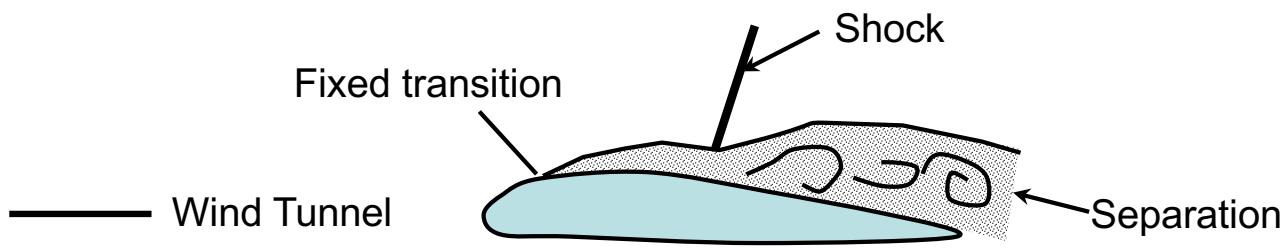
- PURPOSE:
  a) Fix transition from laminar to turbulent at known locations on model.
  b) To insure that the boundary layer is essentially turbulent everywhere downstream of the trip locations to enable wind tunnel data to be extrapolated to flight Reynolds numbers.
- PROCEDURE:
  1. Select location and width of transition trip based on recommendations of Peterson in memo to FSRD dated 11/05/65.
  2. Determine critical height of transition trips with recommendations of Braslow & Knox in NACA TN 4363, 1958.
  3. For configurations and test conditions where shock induced separated flow may occur, consider the recommendations of Blackwell in NASA TN D-5003, Jan. 1969.
  4. At low subsonic speeds, there are some who argue that the free transition condition in the post stall environment gives more meaningful stability and control data.
  5. If using grit, apply to model according to recommendations of Peterson:
     - Narrow roughness band
     - Sparsely distributed grit particles
     - Avoid adhesive buildup during refurbishing.
  6. If using trip dots, follow established procedures.
  7. Check transition strips (grit or trip dots) on a regular basis and refurbish as required.

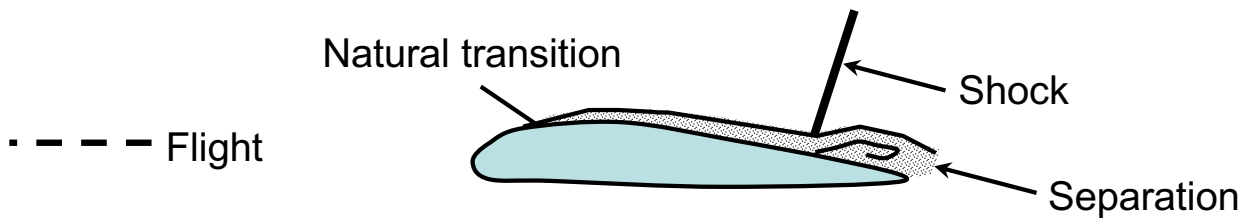
C-141A

M = 0.85, α = 0°



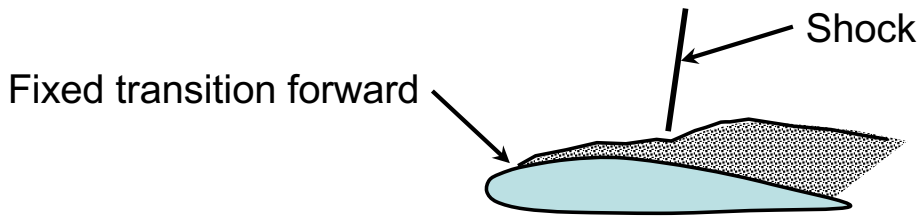




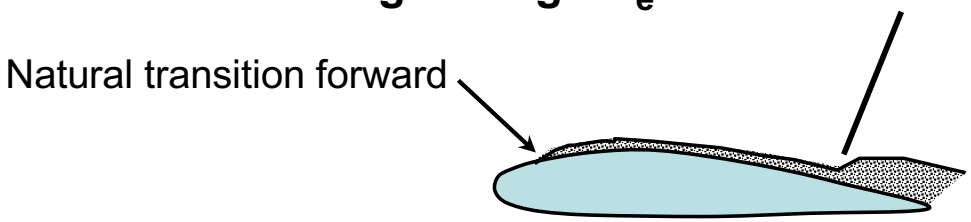


TRANSITION APPLICATION FOR SUPERCRITICAL FLOWS

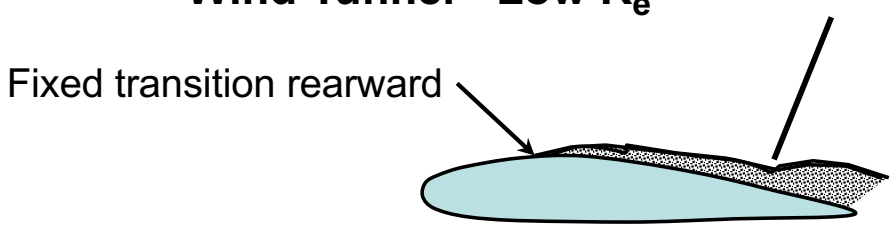
Wind Tunnel - Low R_e



Flight - High R_e



Wind Tunnel - Low R_e



Reference: NASA TN D-5003

MISCELLANEOUS IMPORTANT STUFF

1. Test Notebooks:
   - Good detailed shift notes
   - Leak check records (Be thorough)
   - Describe problems encountered and solutions
   - Sketch devices developed during test (Or you will forget how you did it)

2. Space In Model:
   - Enough internal room to mount instruments with easy access
   - Large passages to route tubes and leads to instruments or through sting

3. Support System Space:
   - Large enough openings into sting for tubes, etc.
   - Large enough hole(s) through sting, adapter, knuckles, etc. to route tubes and leads
   - Externally routed instrumentation may inhibit ability to roll model or change offset hardware
   - Plug sting instrumentation passages with clay of RTV to inhibit flow through the sting between the model interior and model support system

MISCELLANEOUS IMPORTANT STUFF 2

4. Special Hardware:
   - Leveling plates should be an integral part of the model design process
   - Consider having the leveling plate weigh the same as any model hardware that is removed to level the model (i.e., cover plate)
   - Any special calibration fixtures should also be an integral part of the model design process. This would include rigs to calibrate hinge moments of control surfaces.
5. Zero Returns:
   - Monitor zero returns for instrumentation problems
     - Balance zero shifts
     - Plugged pressure orifices
     - Slow (crimped or partially plugged) pressures
6. ESP's:
   - Large enough routing tubes for Ref., Cal., C1, and C2 pressures
   - Place manifolds for above pressures close to modules
   - Independent check pressures on each ESP (One of two ports each)
   - Monitoring scheme so that ESP recalibration need is obvious on CRT display
7. Base Pressure Measurements:
   - For performance testing the model base/cavity pressures are as important as force balance data. Therefore, it is strongly recommended they be hooked up to individual transducers and not be hooked up to ESPs. Therefore, if they are not hooked up to ESPs a decision can be made a any time during the test to shut off the ESPs and continue testing. These pressures should be measured on very accurate transducers whose power supply can be monitored.

SOME OFT HEARD STATEMENTS

- We will calibrate after the test is over.
- All we care about are increments.

EXHAUST SIMULATION TESTING

Presented by
Bob Berrier
4/17/17

OUTLINE - PROPULSION TESTING

- Exhaust Simulation Methods
- Model Design Criteria
  - Propulsion Model Decisions
  - Balance Arrangements
  - Support Systems
- Testing Techniques and Data Trends

EXHAUST SIMULATION METHODS

EXHAUST SIMULATION METHODS

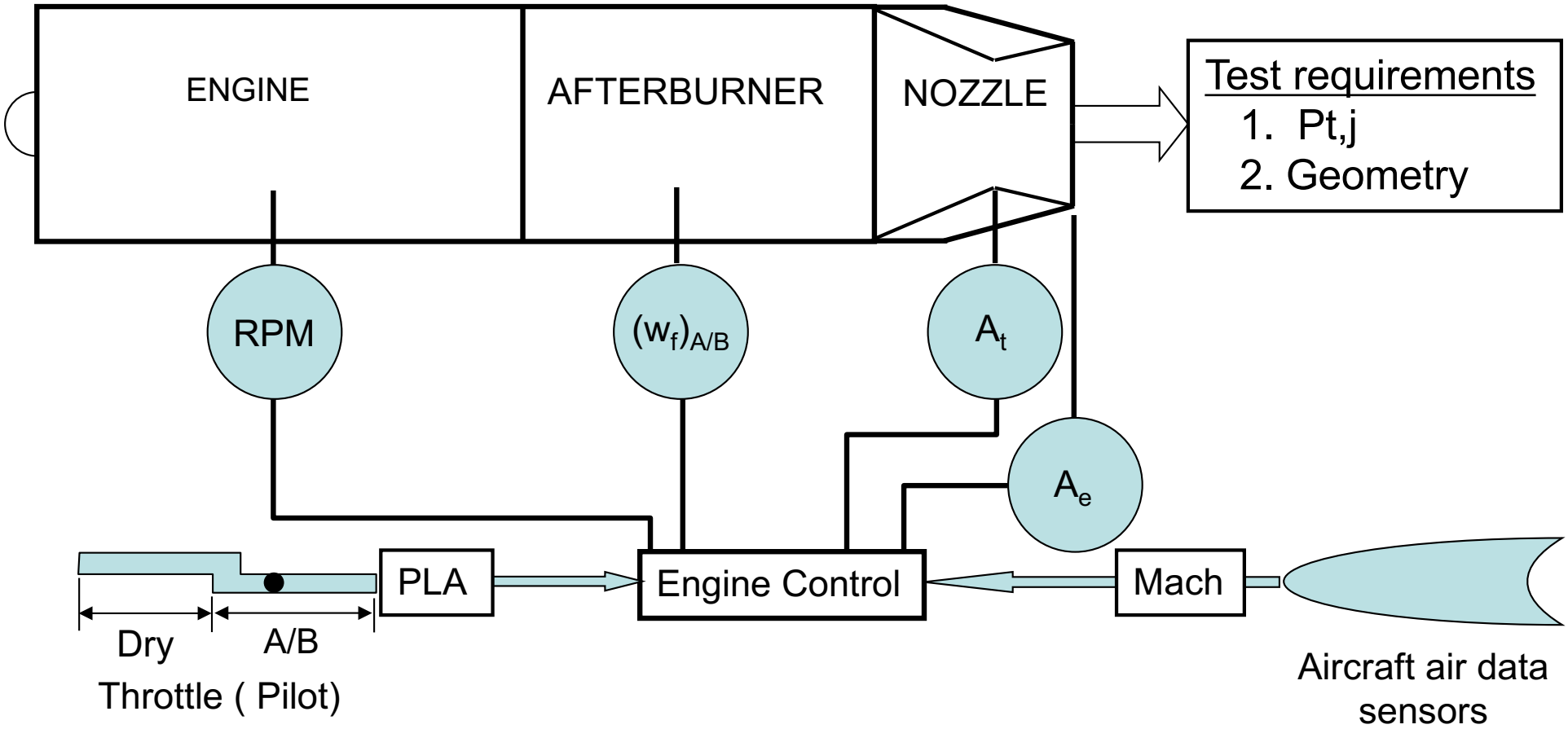
TECHNIQUE	ADVANTAGE	DISADVANTAGE
1. Flow Through	• Low cost • Simulated inlet flow • Realistic upstream flow field for close-coupled propulsion systems (transports)	• Flight NPR not matched • No thrust measurements
2. Plume Simulator	• Low cost	• Plume blockage effect simulated for only one NPR • No jet entrainment • No thrust measurement • Faired-over inlet
3. Air	• Relative low cost • Safe • Reasonable simulation of initial plume angle	• Cold jet - affects downstream plume mixing and shape • Faired-over inlet • Large volume supply lines drives support size up • No heat transfer tests

EXHAUST SIMULATION METHODS

TECHNIQUE	ADVANTAGE	DISADVANTAGE
4. H_2O_2 - Hydrogen peroxide	• Hot jet - good simulation of cruise $T_{t,j}$, plume shape and mixing • Heat transfer tests • Small volume supply lines	• Cost - Model and H_2O_2 • Fire hazard, corrosive • Complex model design • Balance temperature problems • Faired-over inlets
5. Burners Hydrogen Methane, etc.	• Hot jet • Heat transfer tests • Small volume supply lines	• Safety hazard • Temperature impact on model design • Faired-over inlets
6. Turbofan Simulators	• Better matching of both inlet and exit flow conditions	• Does not generally provide simultaneous match of inlet and exit flows • Limits model scale • Complex model, instrumentation • Requires extensive calibrations in special test facility
7. Real Engine	• Exact match of temperature, NPR, plume, chemistry, etc	• Severe limitation on model scale • Complex • Cost • Safety hazard • Purging of engine exhaust

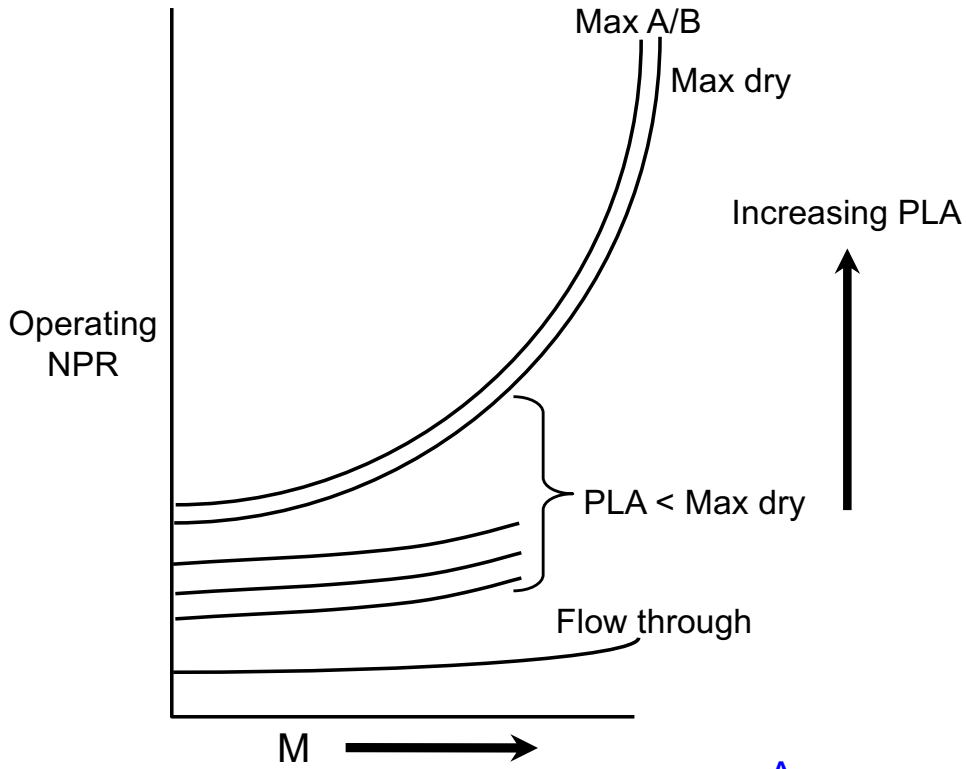
RELATION OF ENGINE/NOZZLE/TEST PARAMETERS

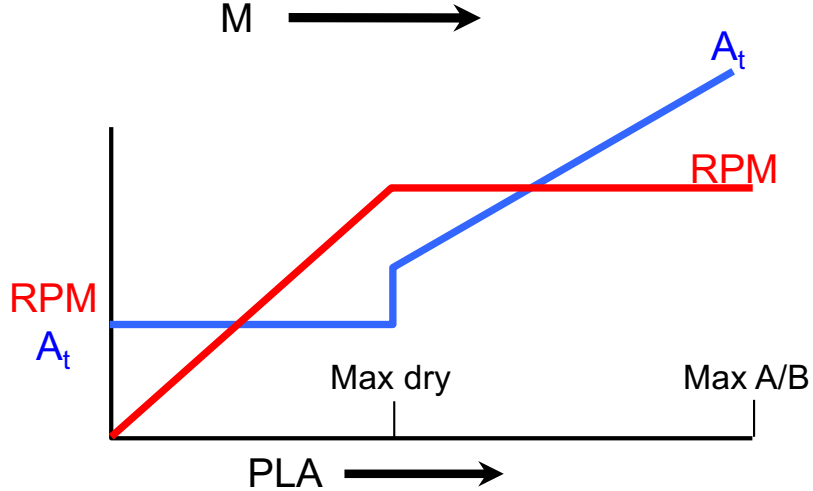
ENGINE/NOZZLE OPERATION



- RPM is a major function of dry PLA; minor function of A/B PLA
- A_t is a major function of A/B PLA; minor function of dry PLA
- A_e is a major function of A_t and Mach; minor function of altitude

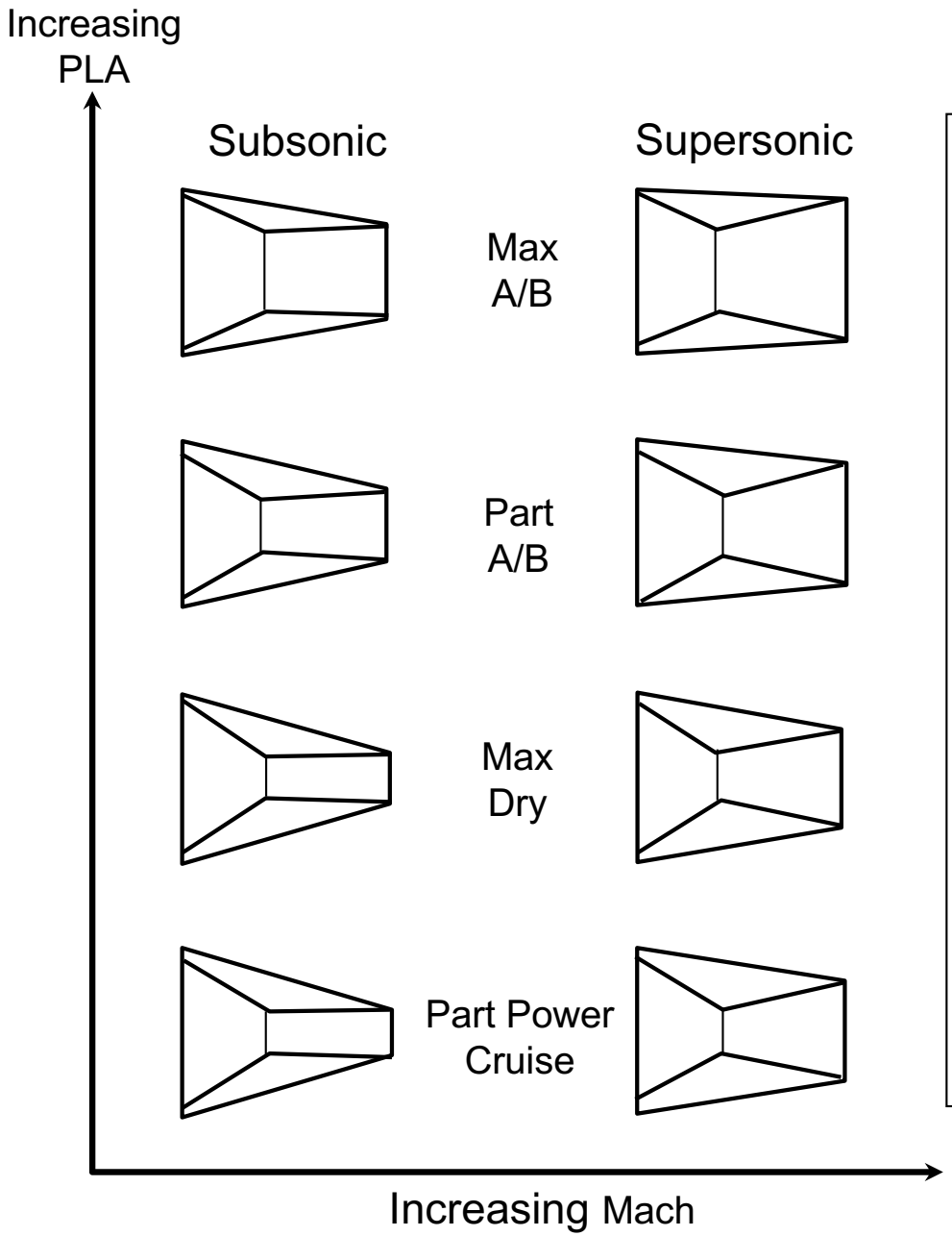
VARIATION OF $P_{t,j}$





- <u>Operating NPR schedule is different for each engine design</u>
- Operating NPR is nearly independent of PLA for max dry and above
- The variation of operating NPR with altitude is small

VARIATION OF GEOMETRY



NOTES

1. Nozzle geometry is nearly independent of PLA during dry power operation
2. A_t increases with PLA during A/B operation
3. A_e / A_t increases with Mach up to mechanical limits
4. A_e / A_t is independent of PLA
   but
   since A_t varies with PLA during A/B operation, A_e must also vary for A_e / A_t to remain constant

SUMMARY OF NPR AND GEOMETRY

1. By testing Max dry geometry over a range of NPR, the entire dry power PLA range can be reasonably simulated.

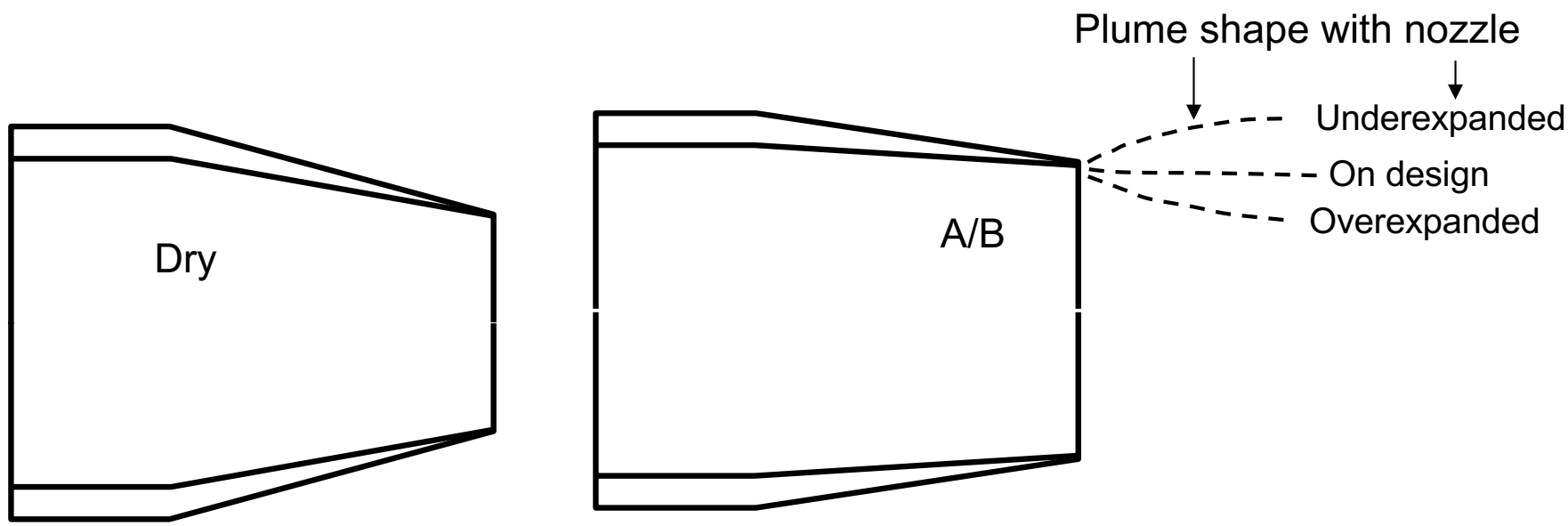
2. By testing two throat areas (generally Max dry and Max A/B), the entire range of PLA can be covered.

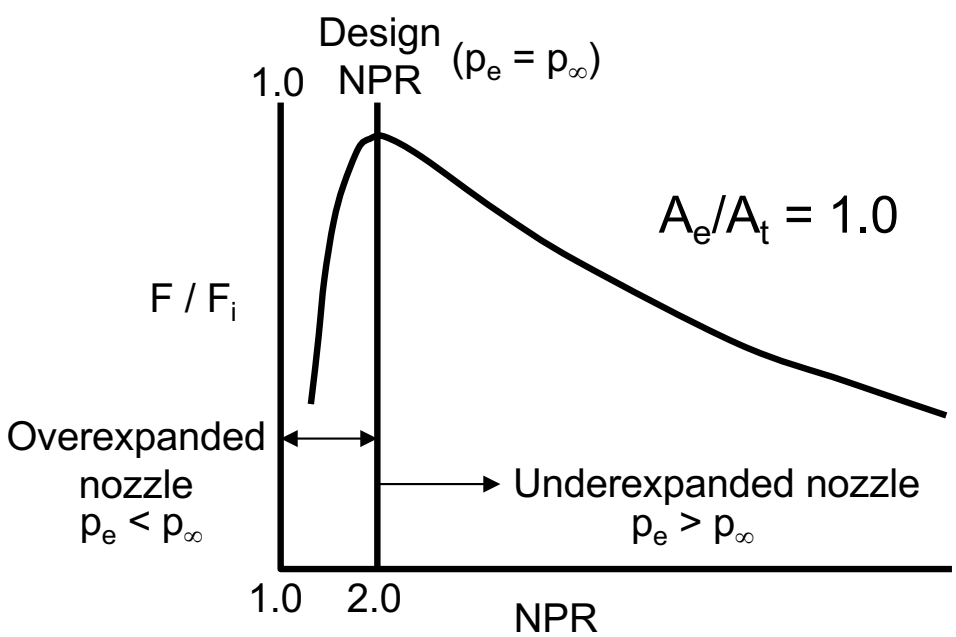
3. By testing two expansion ratios for each throat area, the entire range of PLA and Mach can be covered.

A TOTAL OF FOUR NOZZLE CONFIGURATIONS TESTED OVER A RANGE OF NPR

TYPICAL NOZZLE TYPES AND PERFORMANCE

CONVERGENT NOZZLE





Note:

Design NPR ~ 1.89

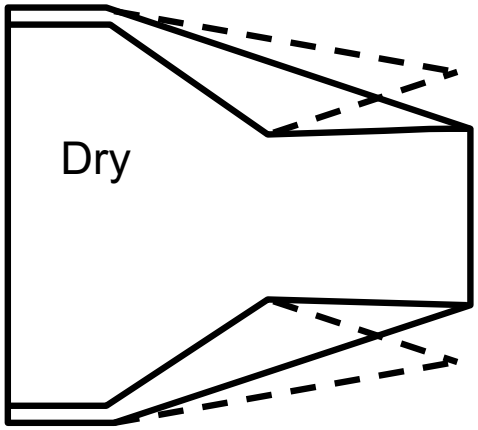
Choke NPR ~ 1.89

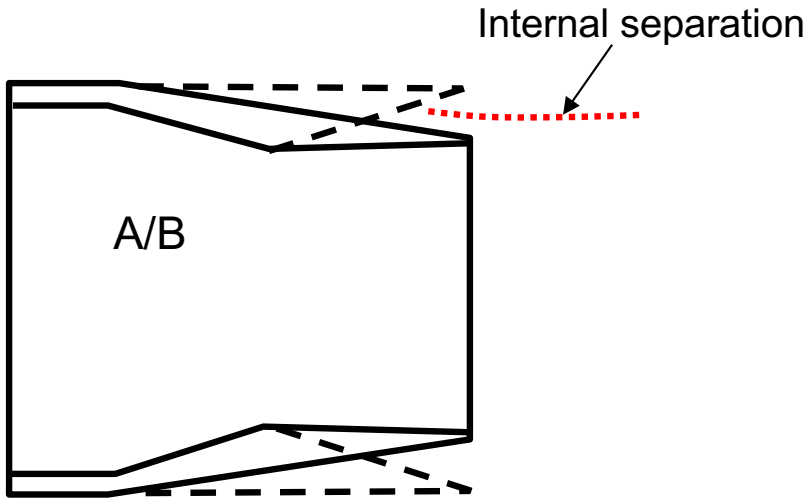
Overexpanded nozzle NPR < Design

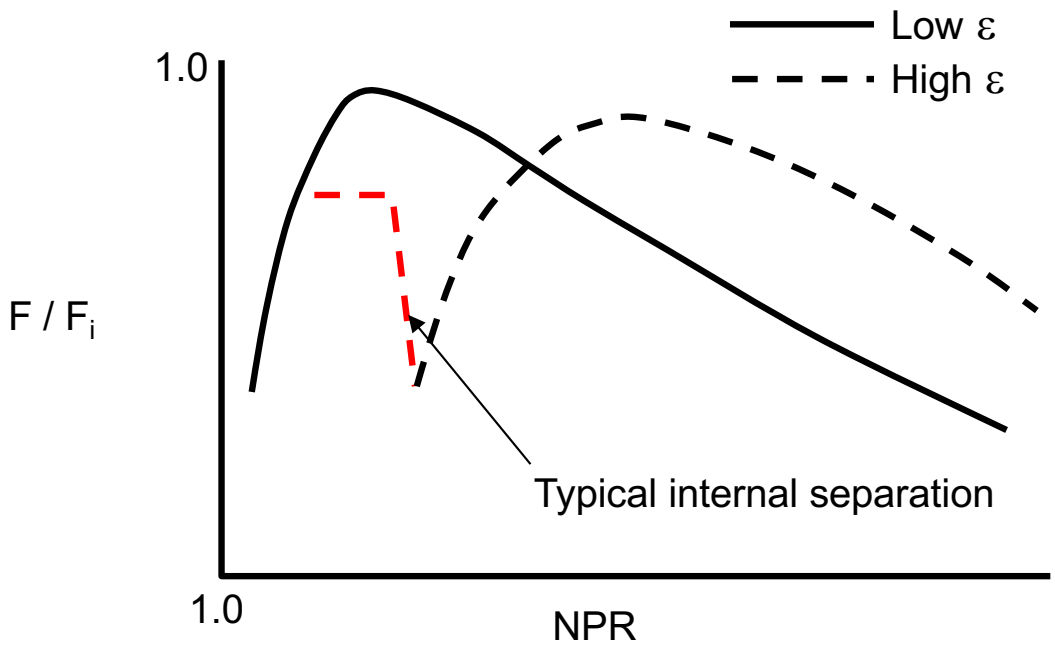
Underexpanded nozzle NPR > Design

Most subsonic aircraft have nozzles of this type.

CONVERGENT-DIVERGENT NOZZLE

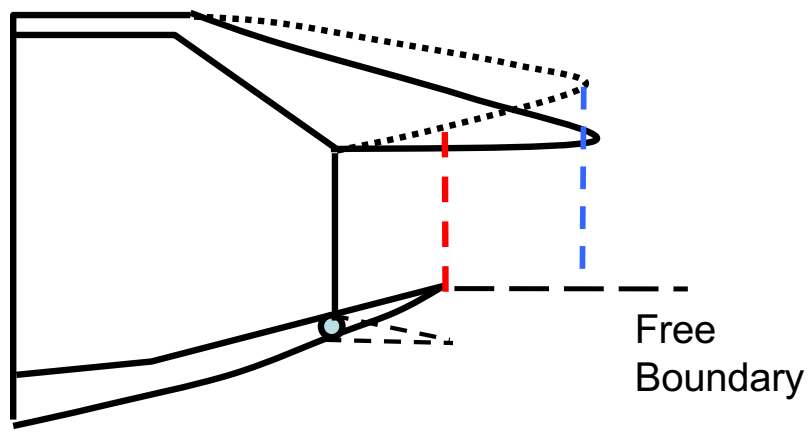


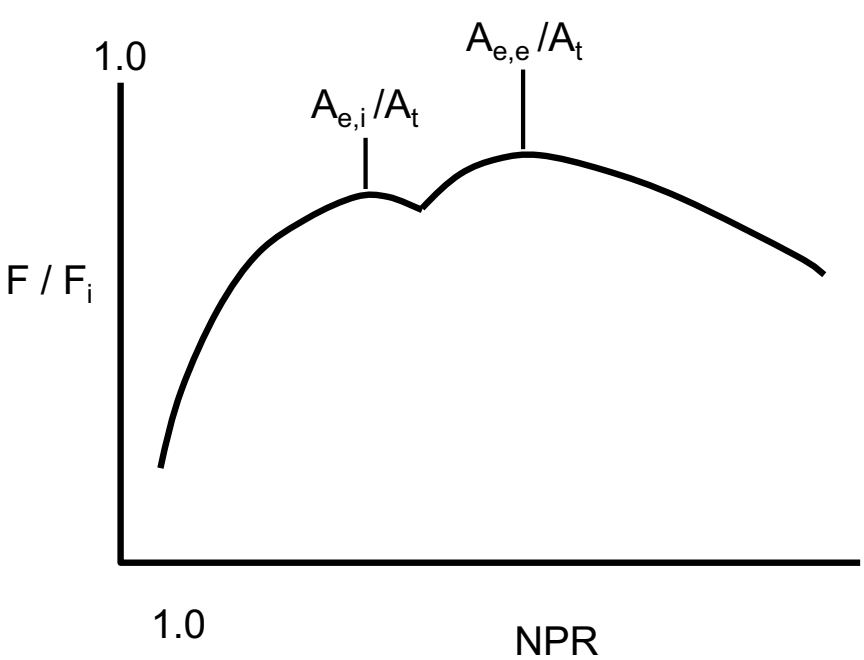




Most supersonic aircraft have nozzles of this type

SINGLE EXPANSION RAMP NOZZLE





Notes:

- Upper flap may be used for vectoring.
- Lower flap may or may not be variable.
- Nozzle may have both an $A_{e,i}/A_t$ and $A_{e,e}/A_t$ and performance trend may have two peaks.
- Since nozzle is not symmetric, nozzle normal force and pitching will be nonzero, vary with NPR and can be quite large. Upper flap variation could be used to trim these forces and moments.
- Nozzle on B-2 and most hypersonic vehicles are of this type.

MODEL DESIGN CRITERIA

EXHAUST SIMULATION MODEL DESIGN CRITERIA

- Model Design Must Meet Aerodynamic, Propulsive and Structural Requirements
- Large Model Size Required to:
  - Accommodate internal propellant lines
  - Incorporate flow transfer devices
  - Have multiple balances
  - Have extensive pressure and temperature measurements
  - Properly scaled nozzle details
- Other Model Size Considerations:
  - Subsonic/transonic blockage
  - Shock reflection length considerations
  - Supersonic shock interference
  - Model loads (Must meet current LHB 1710.3)

Large Tunnels are Generally Required Because of the Size of Powered Models

PROPULSION AERODYNAMICS RESEARCH IS USUALLY A LONG TERM COMMITMENT

- Greater time is involved with complex powered models and often requires multiyear funding
- Construction of a complete powered model (airframe/balance/support) can take up to one year and is very expensive
- Careful assembly, checkout and calibrations are required prior to a wind tunnel test and often require a static test prior to tunnel entry
- For a six-component balance test, installed balance calibrations can last a week or more
- Test programs involve propulsion system variables in addition to aerodynamic variables and can easily last over one month and require multiple tunnel entries

PROPULSION MODEL DECISIONS

- Fully or partially metric?
- 0, 1, 2 or more balances?
- Thrust, Drag, and/or Thrust minus Drag Measurements?

TYPICAL MODEL DECISION PROCESS

- Do I need complete aerodynamics (trim, spillage effects)?
- Do I plan modifications near front of model?
- Do I expect aft-end parametrics to feed well forward?
- Is model close-coupled?
  - Jet/wing interactions, wing-mounted nacelles, jet interactions expected on wing or front of model?

If answer is yes to any one of these, then

FULLY METRIC

If answer is no to all

Based on cost, model availability, balances, etc

PARTIALLY METRIC

FULL OR PARTIALLY METRIC POWERED MODEL

Fully Metric Model

- \+ Measure complete aerodynamics (trim)
- \+ All jet interactions included
- \+ Can make modifications to forward portions of model
- \+ Can be converted to aerodynamic model

- \- High balance loads
- \- Support interference, particularly for pitch
- \- May need to determine support interference effects
- \- Type of metric break seal around strut
- \- Large internal pressure correction to normal and pitch
- \- Potential for fouling problems
- \- May cost more

Partially Metric Model

- \+ Lower balance loads
- \+ Support interference minimized
- \+ Support interference effects do not have to be determined
- \+ Fouling minimized

- \- Complete aerodynamics not obtained
- \- Model modifications usually limited to metric portion of model
- \- Large internal pressure correction to axial

BALANCE ARRANGEMENTS

SINGLE BALANCE

- Thrust: Normally used only for static tests
- Drag: Lower balance loads; greater risk for fouling and balance dynamics; unrealistic base areas
- Thrust - Drag: Higher balance loads; includes external flow effects on thrust; how to separate drag from thrust; lower drag accuracy

MULTIPLE BALANCES

- Thrust - Drag/Drag: Common
- Thrust/Drag: Common
- Thrust-Drag/Thrust: Not common
- Drag/Thrust - Drag: Not common
- Drag/Drag: Not common

PROPULSION MODEL SUPPORT SYSTEMS

PROPULSION MODEL SUPPORTS

1. Same as aero models
   a) Loads
   b) Divergence
   c) Test section position
   d) Alpha/beta requirements
   e) Instrumentation leads

+

2. Must allow geometry simulation in region of interest (inlet/nozzle)

+

3. Must supply exhaust simulation to model

CONFLICT

MINIMUM

SUPPORT

INTERFERENCE

FOR PROPULSION MODELS, SUPPORT SYSTEMS ARE A COMPROMISE BETWEEN REQUIREMENTS`

MODEL SUPPORT TYPES

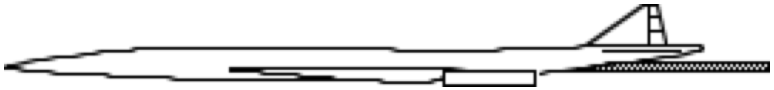
TECHNIQUE	ADVANTAGE	DISADVANTAGE
1. Sting	• Minimum support interference	• Distorts aft-end geometry
2. Annular-flow sting	• No aft-end distortion, particularly for A/B • Small support interference	• Complex arrangement when thrust is measured • Distorts plume shape • Large sting to dry throat ratio
3. Solid plume simulators	• Minimum support interference • Simple/low cost	• Plume blockage effect simulated at only one NPR • No jet entrainment • No thrust measurements
4. Strut/sting-strut	• No aft-end distortion • Exhaust medium supplied to front end of model	• Support interference on aft-end • Significant interference on complete metric model
5. Bifurcated (wing-tip support)	• No aft-end distortion • Exhaust medium supplied to front end of model • Can be used to simulate wings	• Struts (wings) distorted at tip • Doubles isolated model interference • Complete metric model very difficult

MODEL SUPPORT TYPES

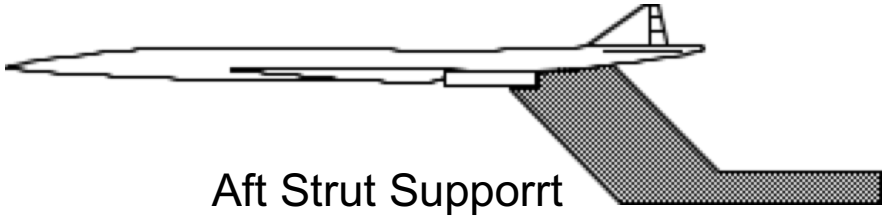
TECHNIQUE	ADVANTAGE	DISADVANTAGE
6. Extended forebody	• No aft-end distortion • Exhaust medium supplied to front end of model • Minimum direct support interference	• Unrealistic boundary layer • Additional complexity to simulate boundary layer • Distorted forebody for complete metric models
7. Semispan from wall	• Larger model scale possible • No aft-end distortion • Ease of bridging balance with exhaust and instrumentation lines	• Wall interference and boundary layer distortions • No yaw capability • Special balances with large yaw component required • Nocross-talk about centerline
8. Semispan model	• No aft-end distortion • Ease of bridging balance • Support simulates wing • Real forebody effects	• Unsymmetric wing distortion • Special balance • Axial metric break and seal • Unknowns (not been done)

MODEL SUPPORT VARIATIONS

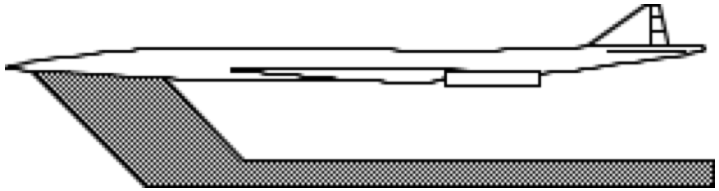
FULLY METRIC MODELS



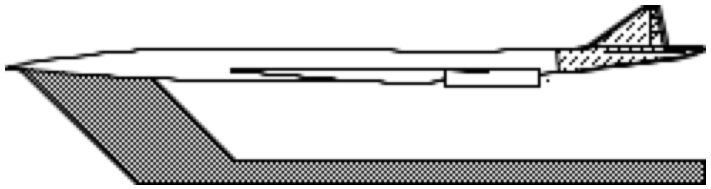
Sting Support



Aft Strut Supporrt

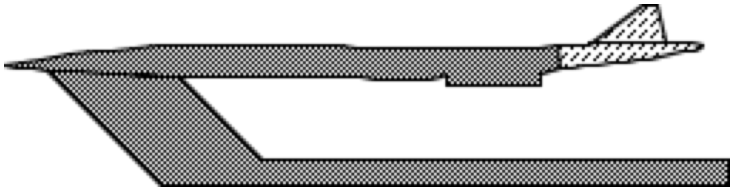


Forward Strut - Single Balance

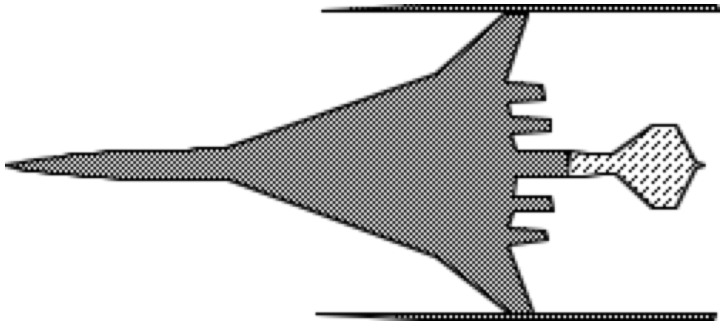


Forward Strut - Two Balance

PARTIALLY METRIC MODELS

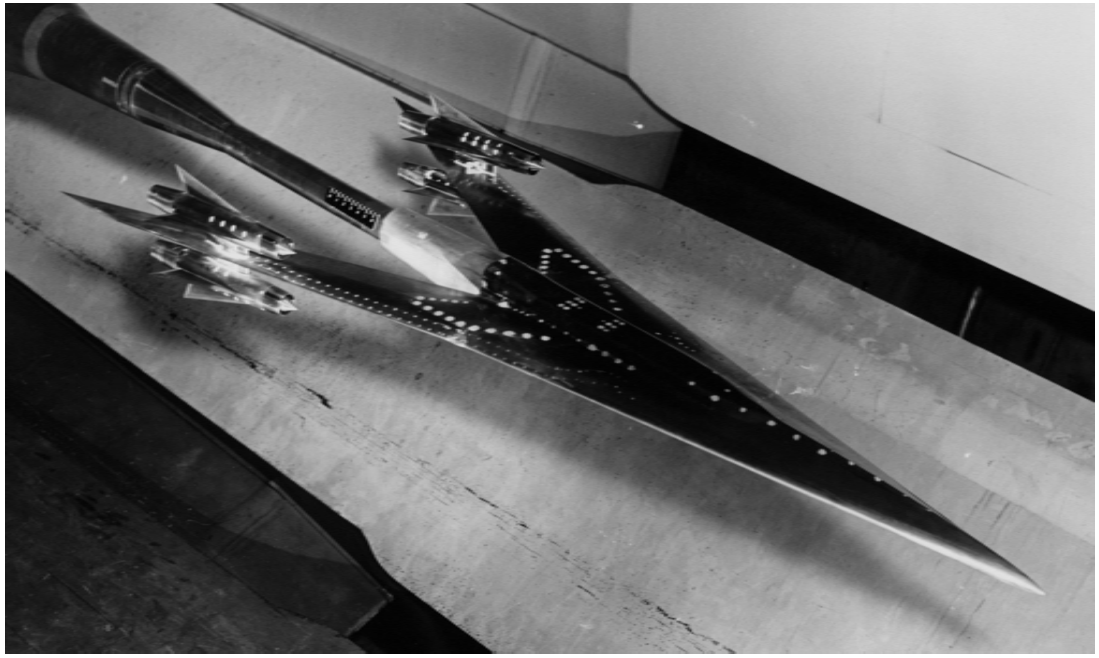


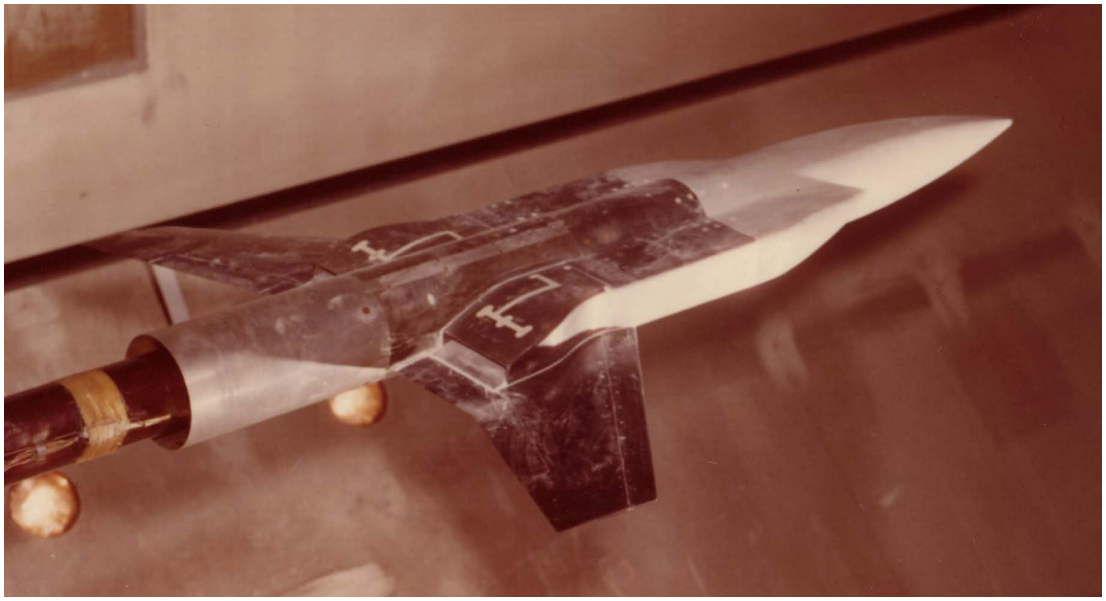
Forward Strut - Single Balance



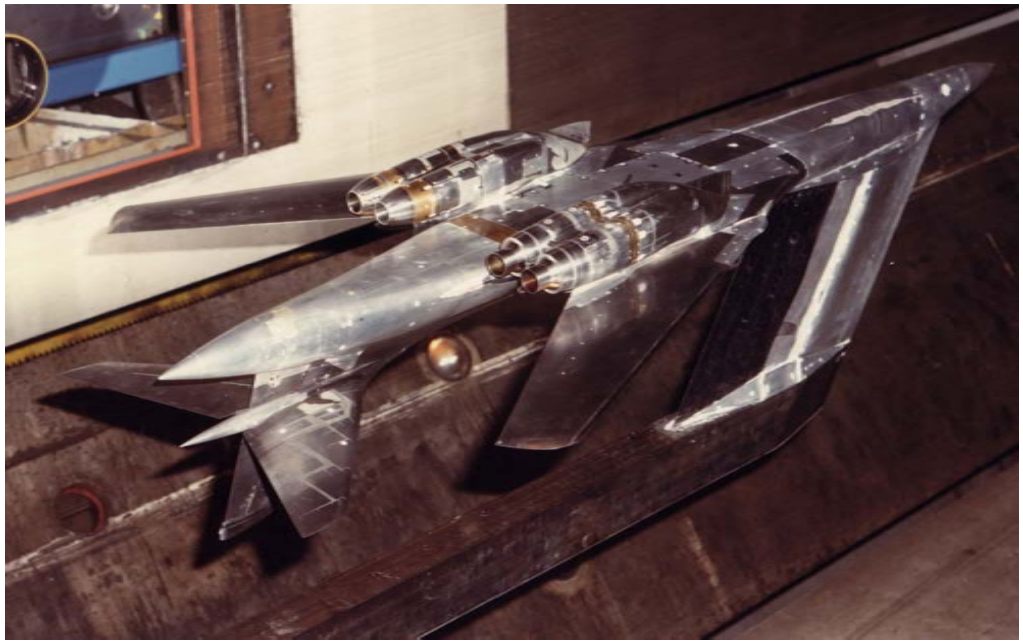
Wing-Tip Support

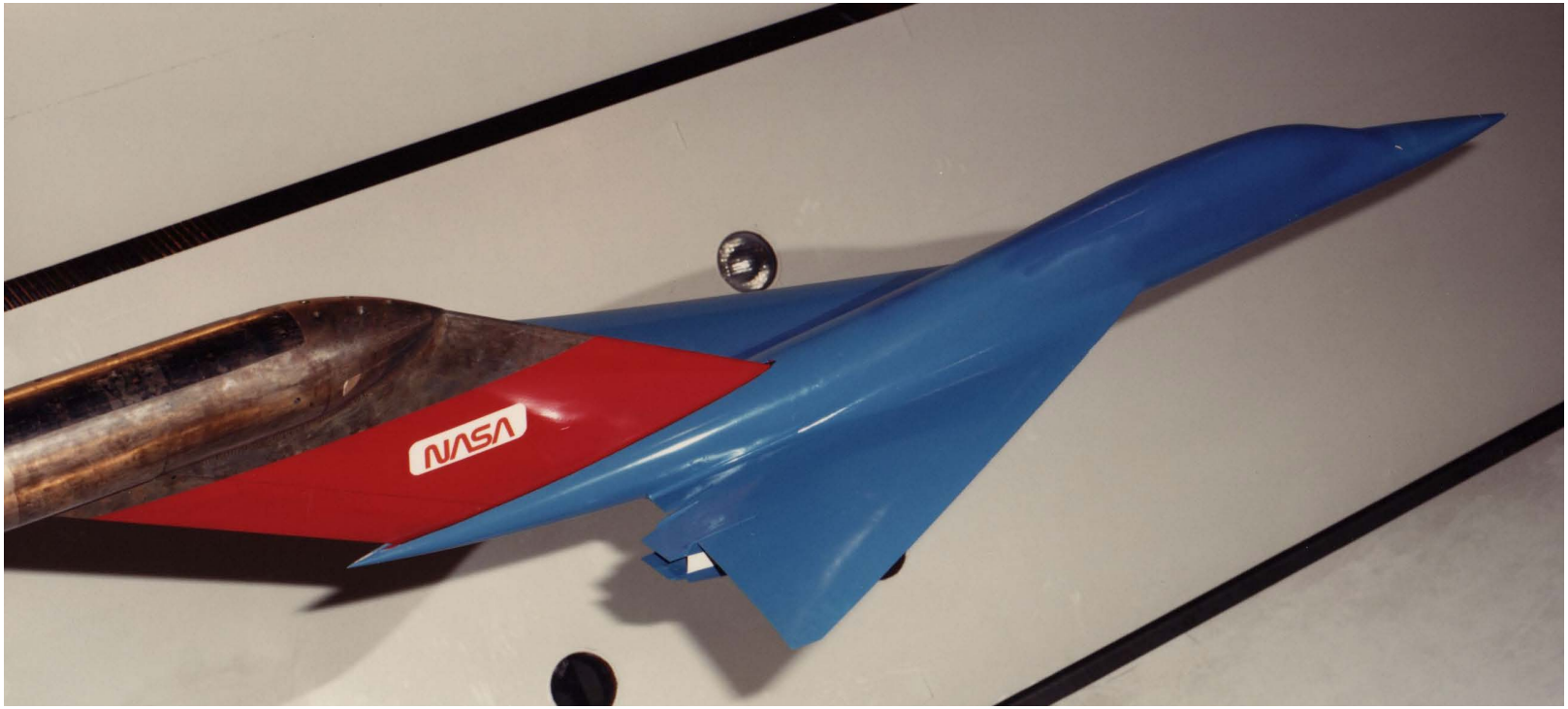
STING-SUPPORT INSTALLATIONS



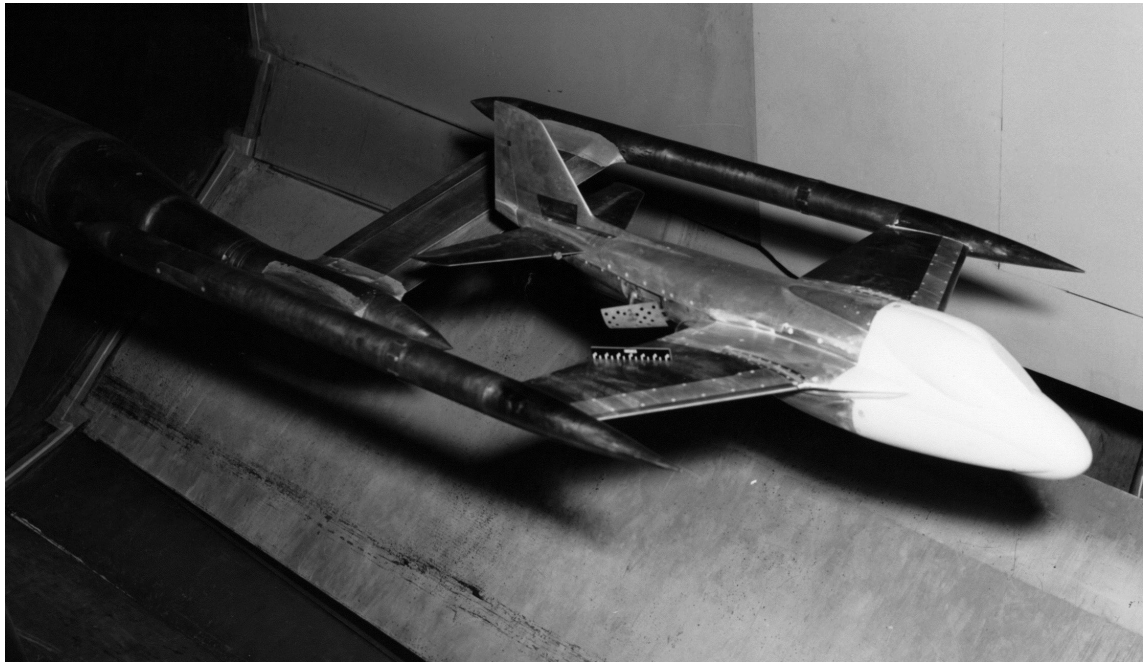


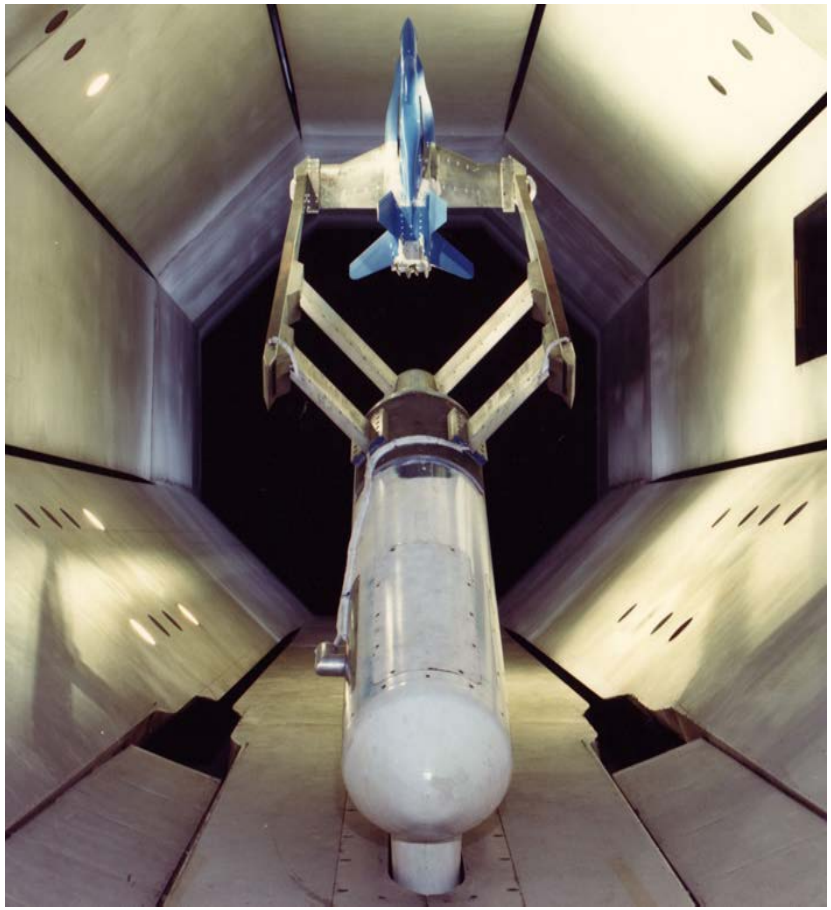
STING-STRUT INSTALLATIONS



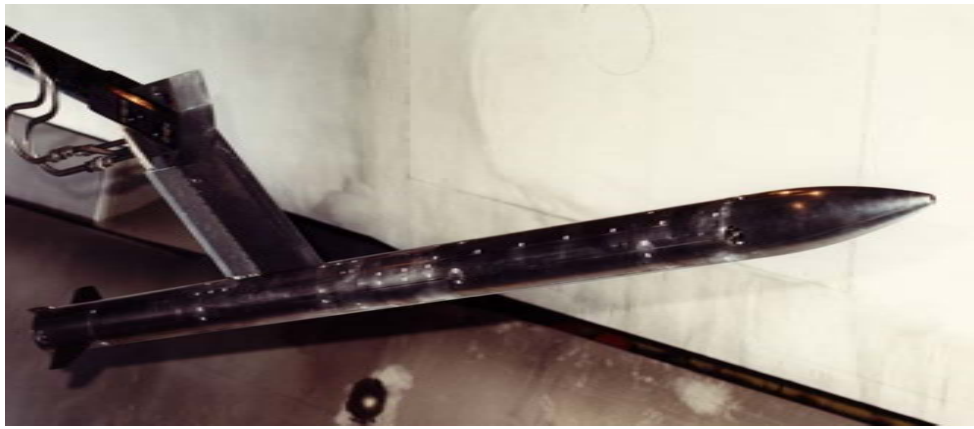


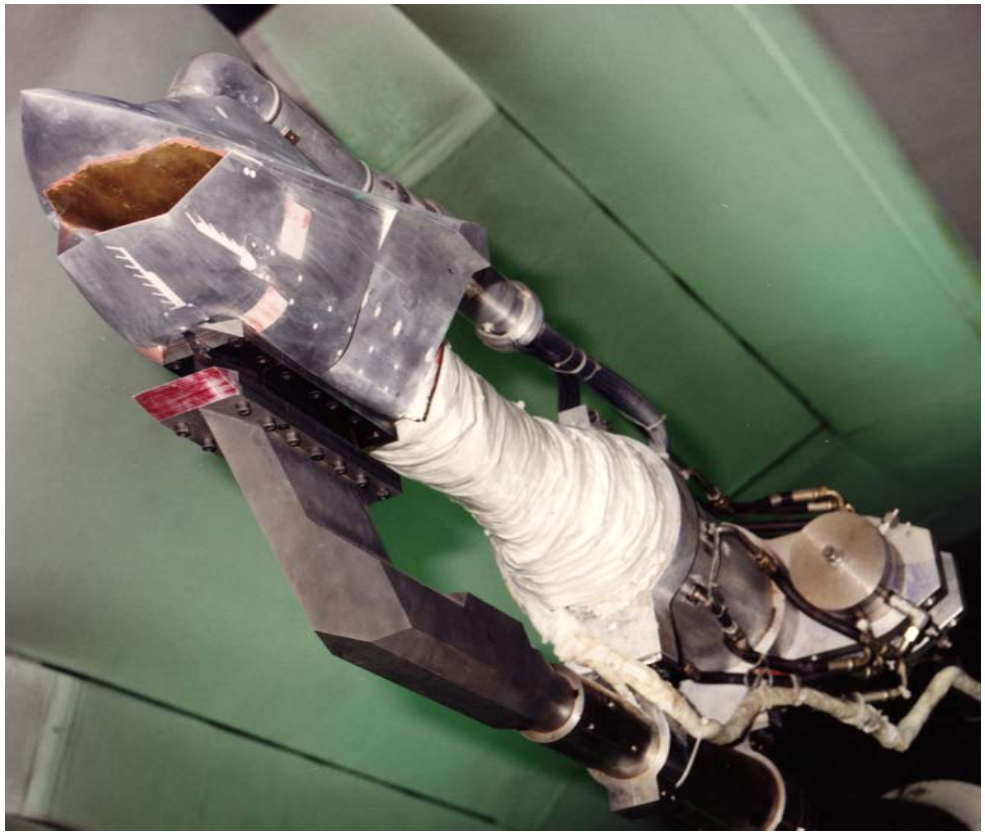
WING-TIP SUPPORT INSTALLATIONS

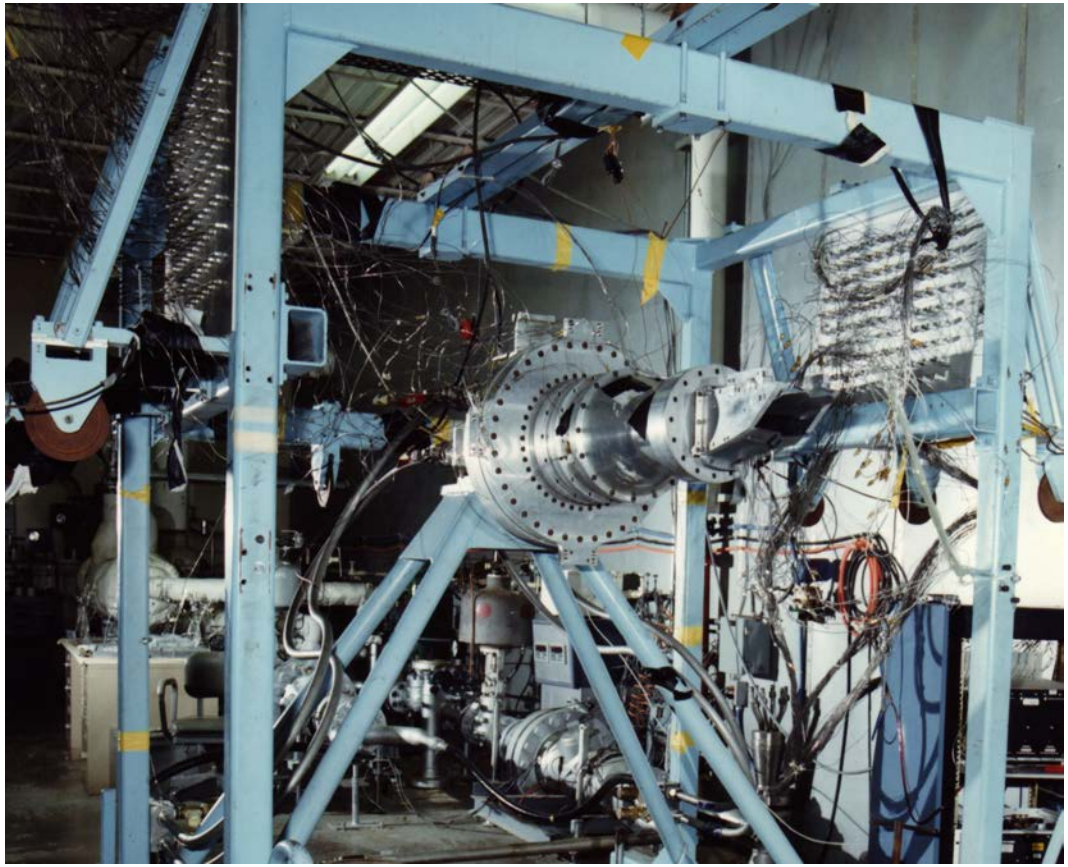




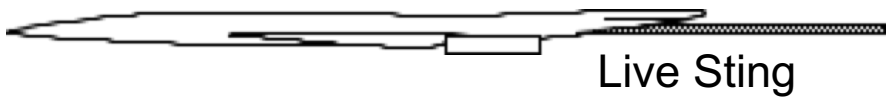
VARIOUS OTHER INSTALLATIONS



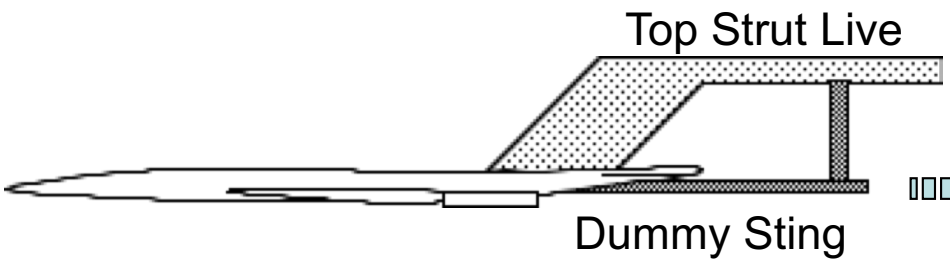




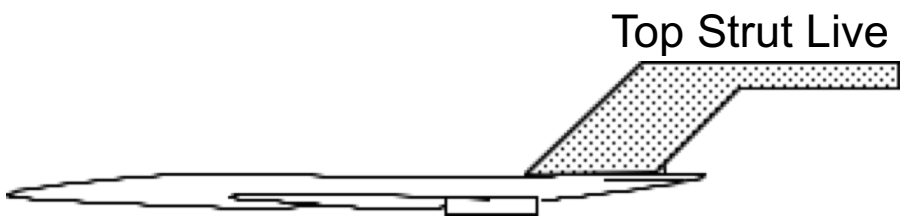
DETERMINE STING SUPPORT INTERFERENCE



- Normal Run
  - Model force or moment
  - Interference of sting on bottom of model



- Tare Run A
  - Interference of top strut on model
  - Interference of sting on bottom of model

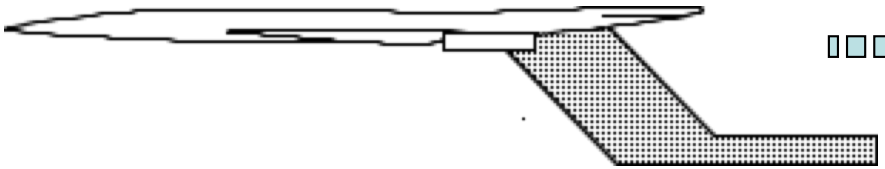


- Tare Run B
  - Interference of top strut on model

Interference of sting = Tare Run A - Tare Run B

Corrected Force = Normal Run - (Tare Run A - Tare Run B)

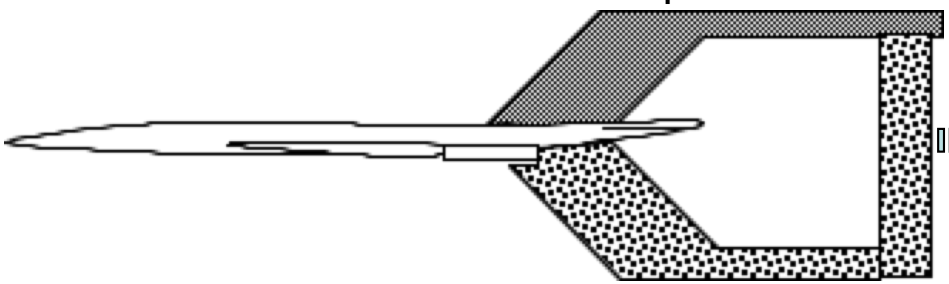
DETERMINE STRUT SUPPORT INTERFERENCE



Bottom Strut Live

- Normal Run
  - Model force
  - Interference of bottom strut on model

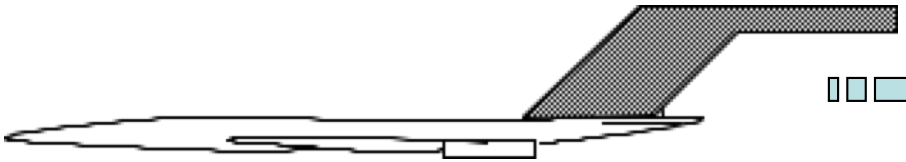
Top Strut Live



Bottom Strut Dummy

- Tare Run A
  - Interference of top strut on model
  - Interference of bottom strut on model

Top Strut Live



- Tare Run B
  - Interference of top strut on model

Interference of bottom strut = Tare Run A - Tare Run B

Corrected Force = Normal Run - (Tare Run A - Tare Run B)

DATA REDUCTION REQUIREMENTS FOR PROPULSION TESTING

Presented by
Larry Leavitt
4/17/17

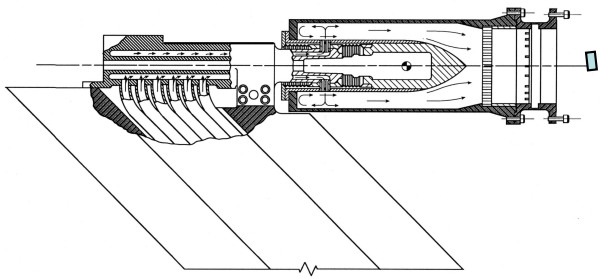
OUTLINE

- Propulsion Tares
  - Propulsion Simulation Systems
  - From Whence We Came, The ‘Good Old Days’
  - Propulsion Simulation Systems Using Twin Bellows
  - Instrumentation/Hardware Requirements
    - Accurate Flow Measurement Apparatus
    - Calibration Hardware
  - Where Do Tares Come From?
  - How Do We Find Them?
  - Description of Various Tares
    - High Restraints
    - Jet-Off Force/Moment Interactions
    - Loading/Blowing Interactions
    - Axial Momentum Tares
- Other Data Reduction Requirements
  - Nozzle Flow Parameters
  - Pressure Coefficients & Integrated Forces
  - Aerodynamic Analysis Techniques (Thrust Removal)

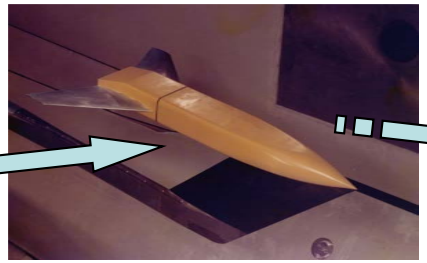
PROPULSION TARES

PROPULSION SIMULATION SYSTEMS

Systems Using Flow Transfer Device With Bellows



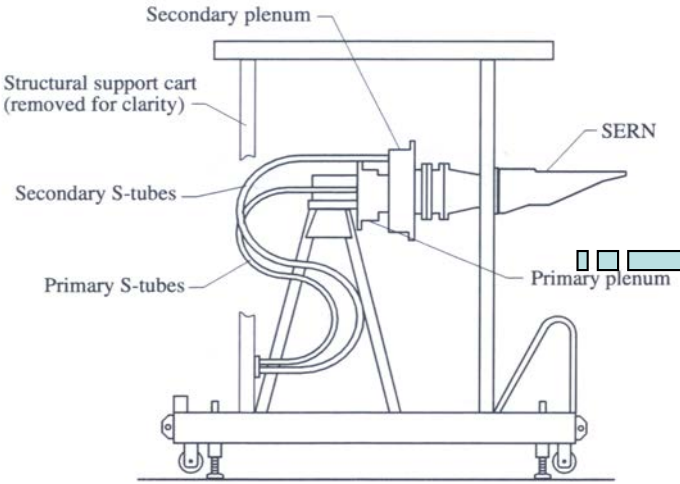
Single Engine/Metal Bellows

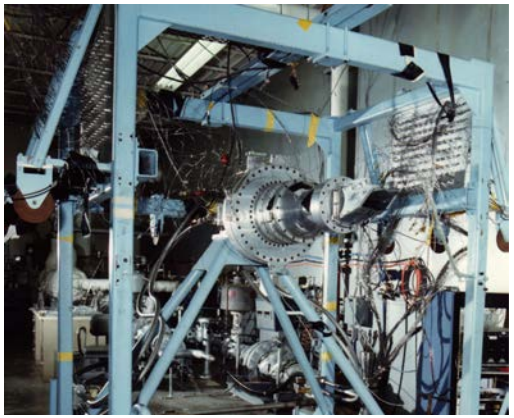


Twin Engine/Metal Bellows

Twin Engine With Metal Bellows
And Plastic Diaphragms

System Using Variation of Long Pipe





Dual Flow Test Stand/S-Tubes

Things That Haven't Worked Well for Us and Other Considerations

- Air transfer systems that bridge metric/non-metric break using hardware that slide or rotate on an o-ring(s) (hysteresis a problem)
- Piston type force balance with labyrinth seals – you modified pressure to remove a delta pressure across the system. Knowing area, one could calculate the force.
- Relying on loose high pressure hoses to bridge the metric/non-metric break (hysteresis and other uncertainties like strut movement)
- We never had much luck with flow thru force balances (Others have. 16TT temperatures may have been the problem)
- Some systems are very susceptible to differences in external flow temperature and internal flows (propulsion simulation air).

Note: any system that produces gradients of different temperatures across different portions of the force balance give problems.

Goal: A repeatable (yet flexible) means of getting high pressure air (or other propulsion simulation medium) across the metric/non-metric break

FROM WHENCE WE CAME!

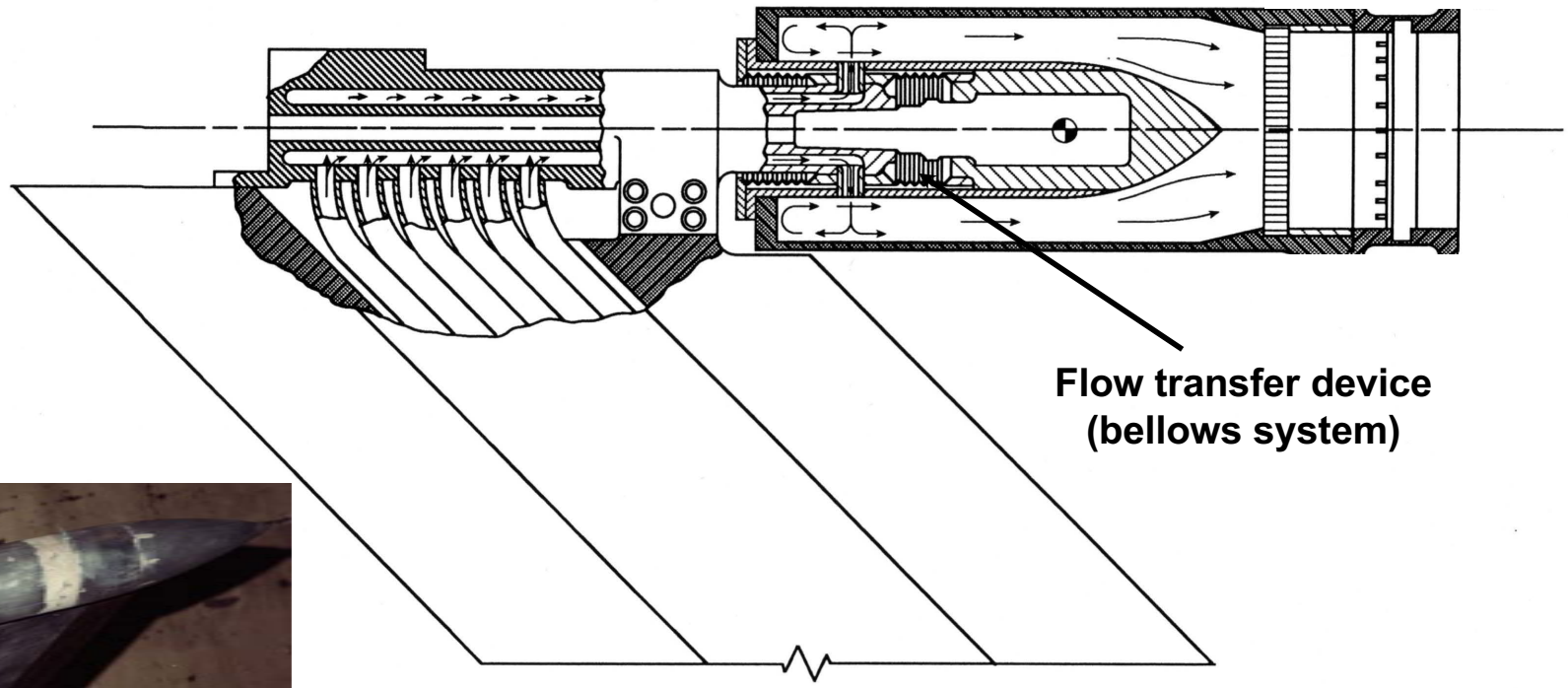
- Early Days of Propulsion Testing (Late 1960s)
  - Original air-powered system mounted on a fixed strut (from tunnel floor) was a replacement for a H_2O_2 hot-jet system that was put into operation in early 1950s
  - Could only test at zero angle of attack
  - Only momentum corrections were required
  - Weight flow measured with rotary type flow meters (low accuracy because frequency converter needed to determine weight flow)

- Mid Technology (Mid 1970s)
  - Model mounted on a sting-strut that provided angle of attack variation
  - Realization that blowing/loading tares important with the advent of vectored thrust research
  - Found during testing of new twin-jet powered model designed for thrust vectoring
  - Mostly 3 component testing
  - Multiple Critical Flow Venturi System put in operation with the capability to measure flows from 1 lb/sec to 40 lbs/sec. This system depends only on a single pressure measurement.

- Latest and Greatest (1980s - ?)
  - Continuous improvements and refinements as testing requirements increased
  - 6-component corrections necessary for testing multi-axis thrust vectoring nozzles
  - Automated data reduction technique for determining tare constants put in operation

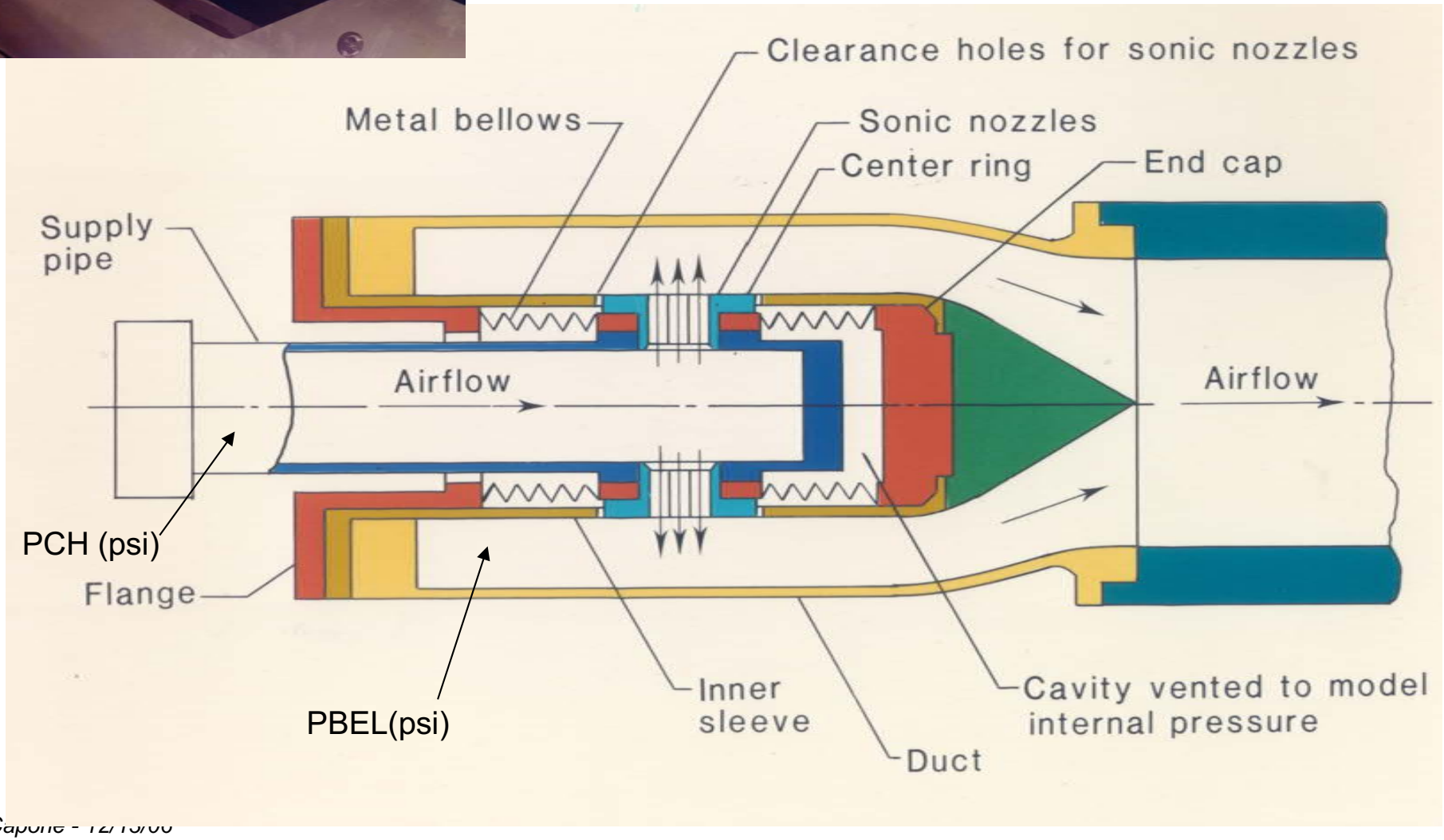
PROPULSION SIMULATION SYSTEMS WITH BELLOWS FLOW TRANSFER DEVICES

SINGLE-ENGINE PROPULSION SIMULATION SYSTEM



- Workhorse propulsion simulation system developed in late 1960s to replace H_2O_2 hot jet system
- Featured a unique, compact, twin-bellows flow transfer device designed to eliminate momentum tare forces
- Used continuously in the 16-Foot Transonic Tunnel and Jet-Exit Test Facility from 1968 to 2005.

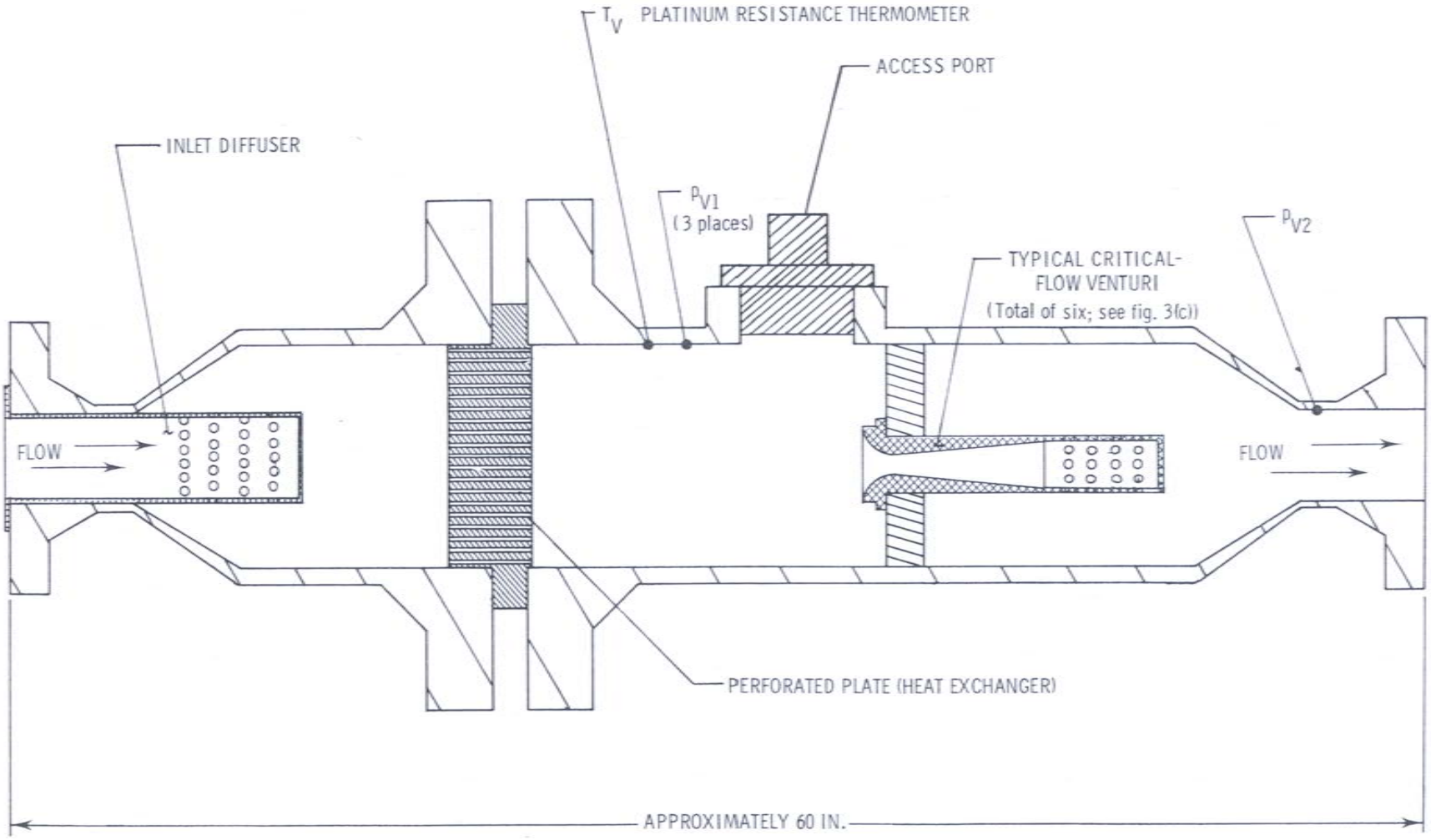
TWIN-ENGINE PROPULSION SIMULATION SYSTEM



INSTRUMENTATION/HARDWARE REQUIREMENTS

A VERY ACCURATE FLOW MEASURING SYSTEM REQUIRED

Multiple Critical Flow Venturi System

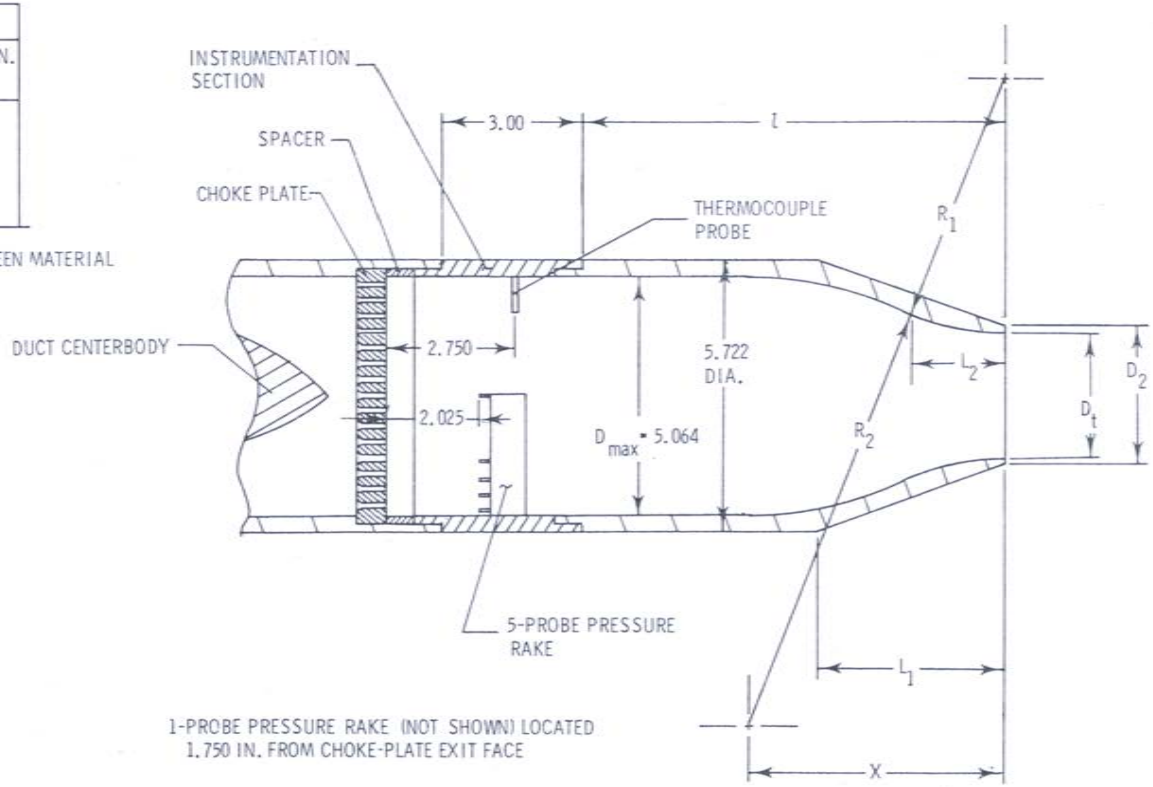


STRATFORD CALIBRATION NOZZLES

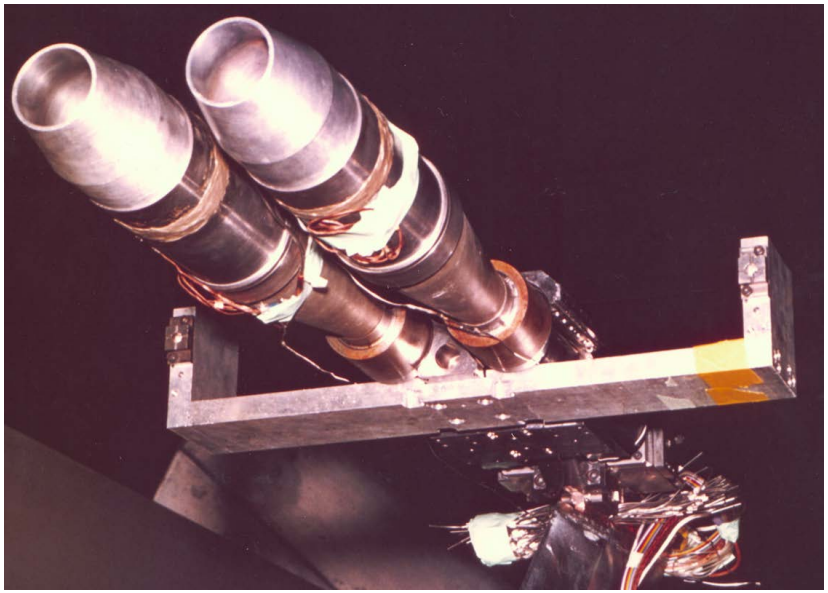
STRATFORD CHOKE NOZZLES								
MEASURED THROAT AREA (IN.^{2})	DESIGN GEOMETRY							
	R_1, IN.	R_2, IN.	X, IN.	D_t, IN.	D_2, IN.	L_1, IN.	l, IN.	L_2, IN.
0.999	2.257	21.314	9.428	1.128	1.378	5.500	11.88	0.903
1.933	3.140	9.000	6.274	1.569	1.820	4.000	9.00	1.623
3.002	3.909	14.715	7.450	1.955	2.204	4.500	9.00	1.564
3.992	4.510	8.320	5.837	2.255	2.505	4.000	9.00	2.052
5.711	5.400	7.700	5.432	2.700	2.950	4.000	9.00	2.239
8.501	6.580	7.868	4.985	3.290	3.540	4.000	9.00	2.270
11.352	7.600	5.900	4.086	3.800	4.050	3.500	9.00	2.300

CHOKE PLATES		
OPEN AREA (IN^2)	PERCENT DUCT AREA	HOLE DIA., IN.
1.750	2.7	0.098
3.853	19.1	0.147
5.779	28.0	0.180
7.549	37.1	0.206
15.286	75.9	

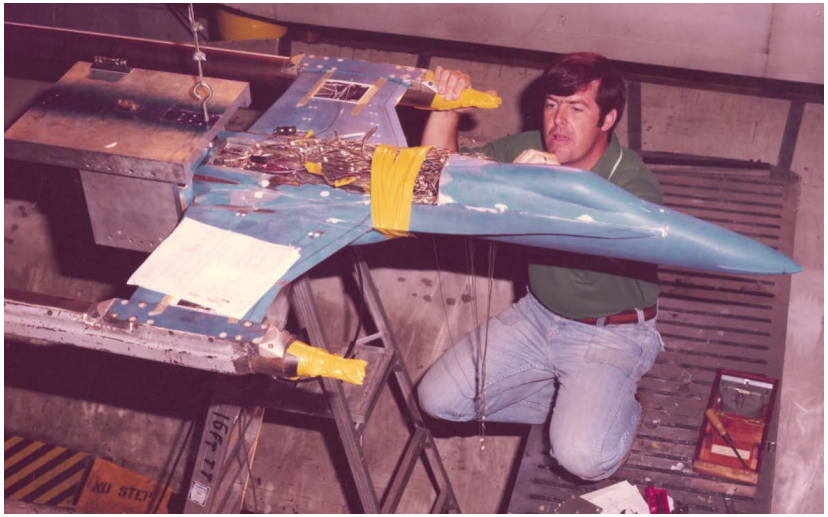
NOTE: 15.286-IN^2 CHOKE PLATE IS ACTUALLY WIRE SCREEN MATERIAL SUPPORTED BY AN OPEN METAL LATTICEWORK



CALIBRATION HARDWARE NEEDS TO BE PART OF BASIC MODEL DESIGN



Twin Jet Model with Stratford Nozzles

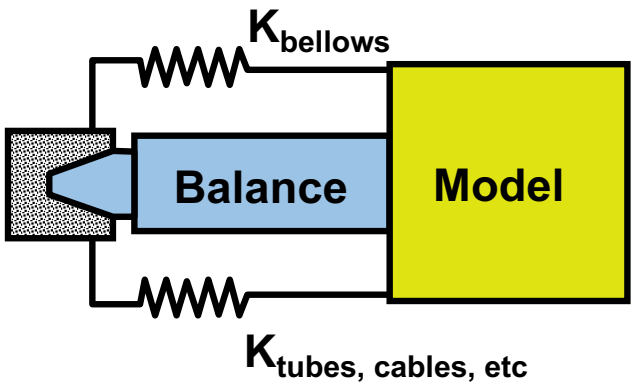


F-18 Model with Calibration Fixture

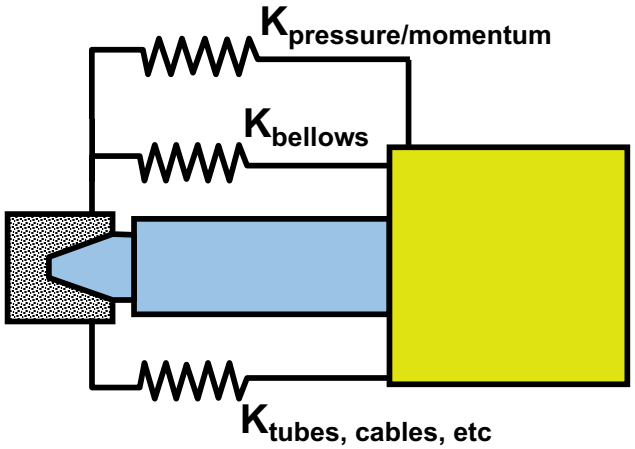
WHERE DO TARES COME FROM?

TWO TYPE TARES NEED TO BE DETERMINED

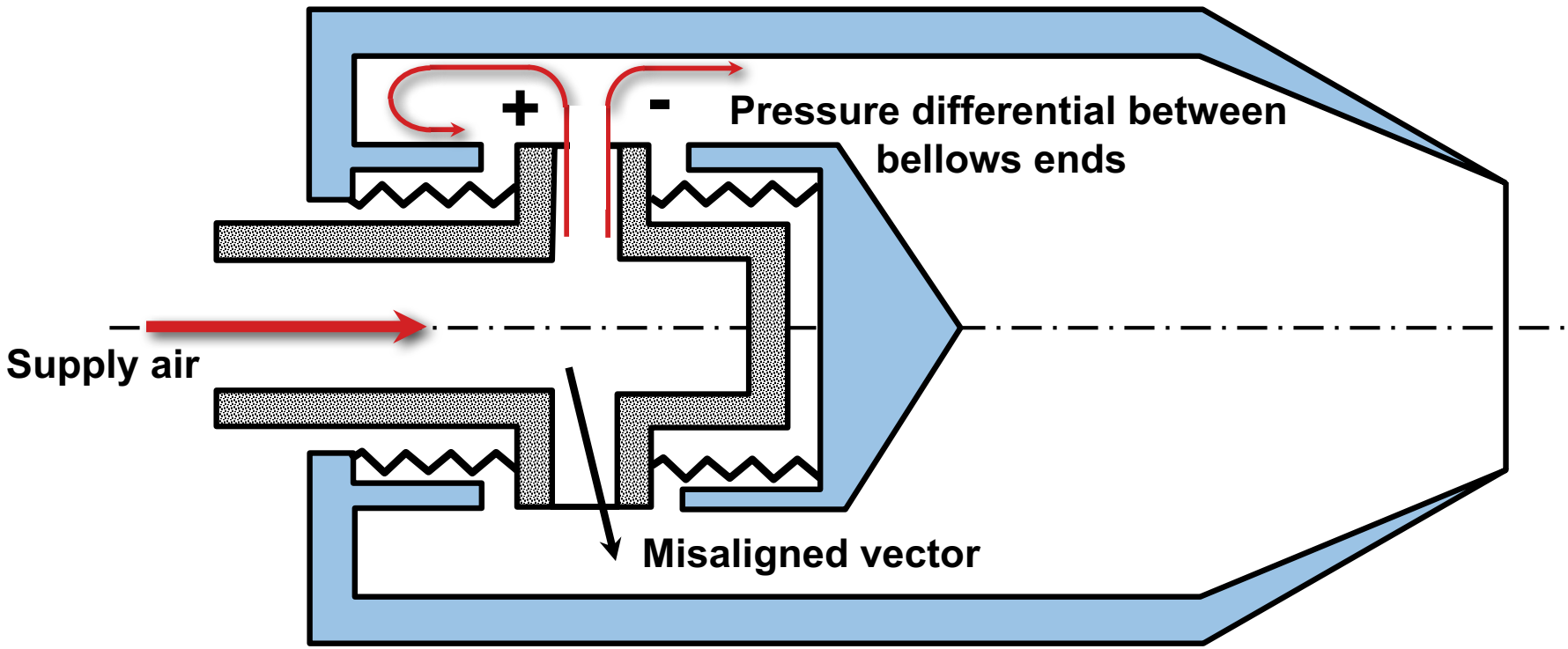
- **JET-OFF TARES**
  - Changes in the spring constant of the balance resulting from the Flow Transfer Device (bellows assembly), steel tubing, cables, etc. bridging the metric and nonmetric portions of the model



- **JET-ON TARES**
  - Changes in the spring constant of the bellows resulting from pressurization of the bellows, local pressure differences from one end of the bellows to the other, and misalignment of the momentum transfer vector



MOMENTUM TARE FORCES



HOW DO YOU FIND THEM?

THREE THINGS YOU MUST KNOW OR DETERMINE

- Tare Free Balance Characteristics
  - Bare balance calibration
- Effect of Restraints Across Balance at Jet-off Conditions:
  - Loading calibration of balance with fully assembled model including all tubing, cables, etc.
- Effect of Bellows Pressurization and ‘Flowing’ Restraints Across Balance at Jet-on Conditions:
  - Loading/blowing calibration of balance with fully assembled model including all tubing, cables, etc.

PROPULSION TARES CALIBRATION PROCEDURE

- System Leak Check -- **NO** Leak Is a Good Leak!
- Perform Jet-Off Balance Loadings
  - All components of interest
- Perform Jet-On Balance Loadings
  - All components of interest
  - Over expected range of loads, bellows pressure and throat areas
- Perform Axial Momentum Tare Runs
  - Over expected range of throat areas

TYPICAL BALANCE LOADINGS CONSIDERATIONS

- Provide as many loads possible by hanging because pulleys often provide hysterisis problems

- Loadings should be carefully directed through the balance moment reference center. Be sure your loading fixtures are properly placed and model is level at each point (unless pulleys are attached to the model support system)

- Hang all loads to expected maximum values. If expected maximum values are unknown, load to the balance limits. (Positive and negative loadings were suggested for the automated tare program)

TYPICAL LOADING/BLOWING MATRIX

Example shown for Normal loadings

Normal	NPR	Cal Nozzle Area
0	1.0 (JET-OFF)	4, 6, 8, etc
200		
400		
600		
800		
0		
0	1, 2, 4, 6, 8, 1	
200		
400		
600		
800		
0		
0	1.0 (JET-OFF)	
-200		
-400		
-600		
-800		
0		
0	1, 2, 4, 6, 8, 1	
-200		
-400		
-600		
-800		
0		

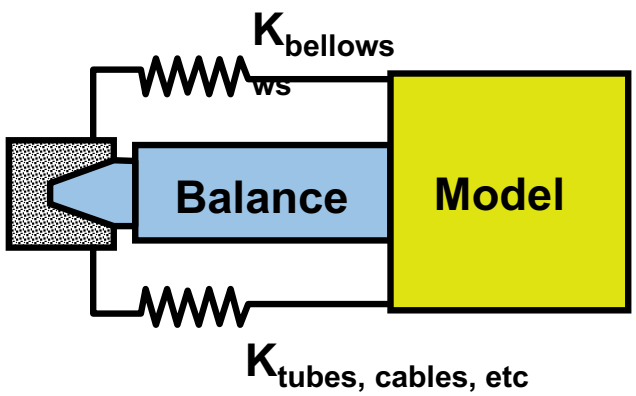
- As needed load:

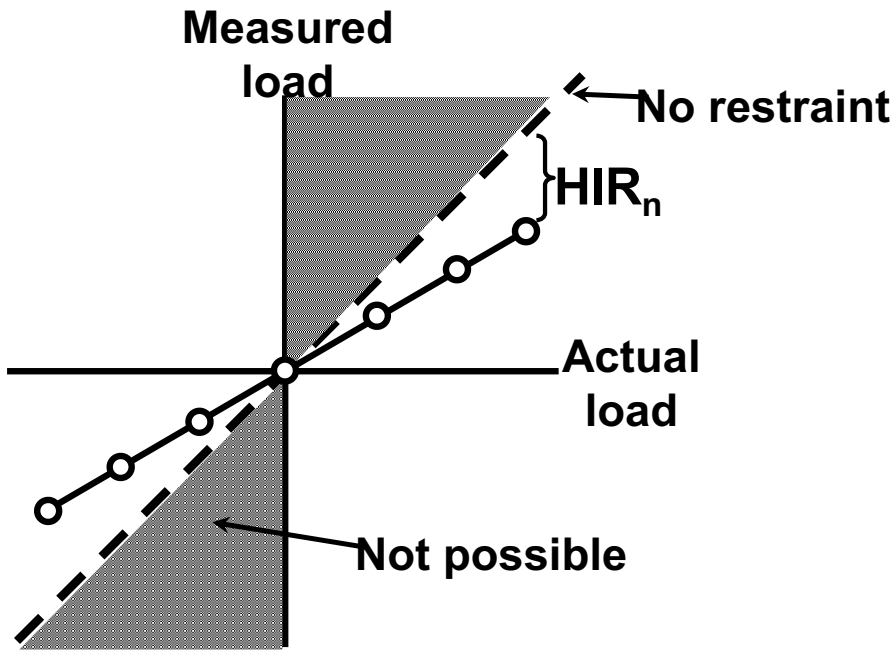
  ± Pitch, ± Roll, ± Yaw, ± Side

- Typically pitch, roll and yaw are loaded by transfer of weights. For example, would have constant NF while PM varies
- Roll tares may be questionable because bellows do like to be twisted

DESCRIPTION OF VARIOUS TARES

HIGH RESTRAINTS



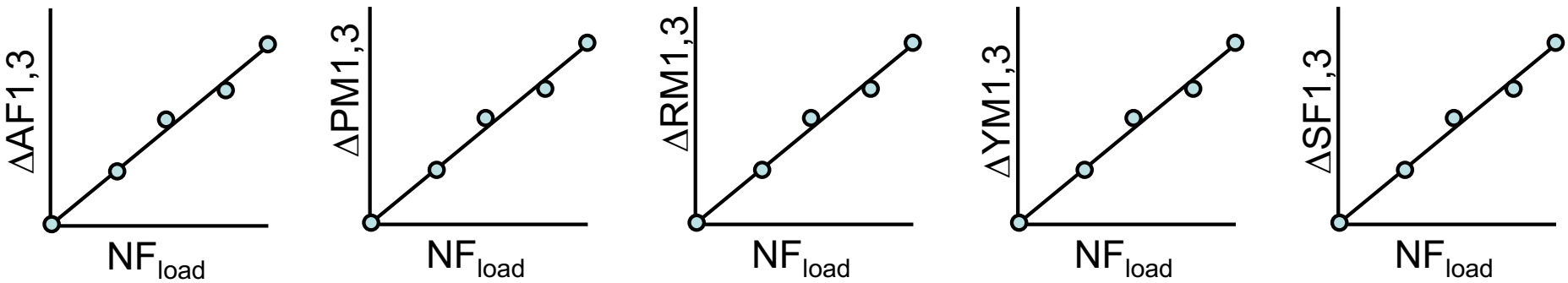


$$HIR_n = \frac{\text{Measured sensitivity constant}}{\text{Balance sensitivity constant}} - 1$$

- High restraint constants account for the loss in component sensitivity due to additional "spring constants" across the balance.
- For a given load, millivolt output will be less for the installed balance than for the bare balance.
- High restraints constants ***<u>SHOULD ALWAYS BE POSITIVE</u>***

JET-OFF FORCE/MOMENT INTERACTIONS

Example: Determine Normal Force Tares for 6 Component Test

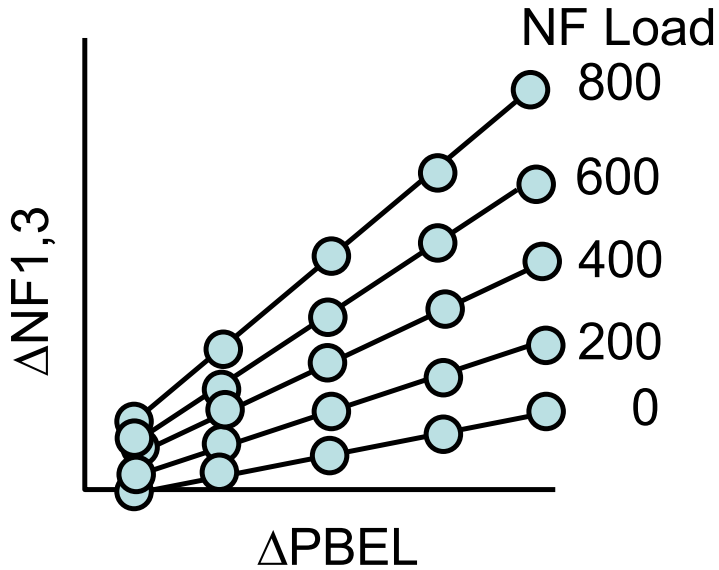


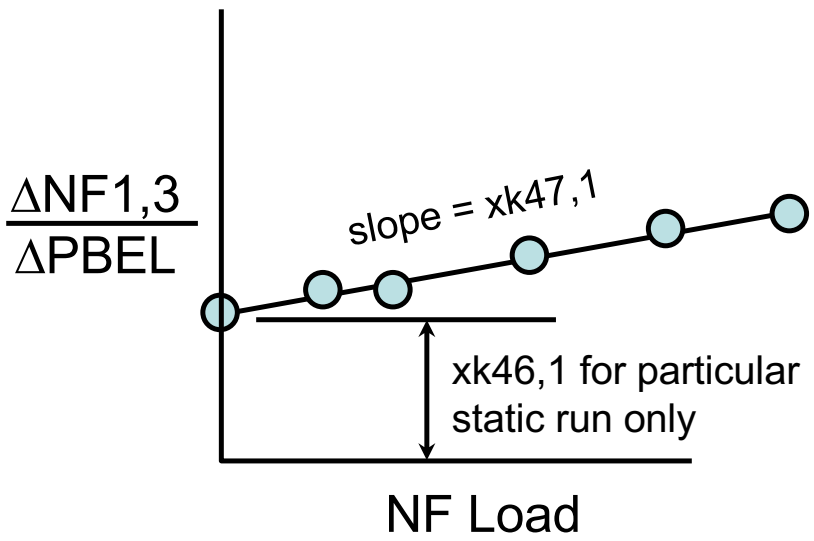
Where: $\Delta AF1,3 = AF1,3_{NFload} - AF1,3_{NF=0}$, $\Delta PM1,3 = PM1,3_{NFload} - PM1,3_{NF=0}$, etc.

- Compute jet-off runs with high restraint constants and XK's = 0 and KMOM = 2 to determine tares.
- For a 3 component test, need to look at effects of:
  - NF on AF and PM
  - PM on AF and NF

LOADING/BLOWING INTERACTIONS

Example: Determine Normal Force/Air Effects on NF Tare for Particular Calibration Nozzle





where $\Delta NF1,3 = NF1,3_{JET\ ON} - NF1,3_{JET\ OFF}$, etc.

- Compute all runs with high restraints and jet-off constants with correct weight flow.
- The effects of NF/Air on DPM, DRM, DYM, DSF must also be determined.
- Likewise, the effects of PM/Air, RM/Air, YM/Air, and SF/Air on all balance must be computed as required
- Recompute data, ***CHECK RESULTS***, iterate

Typical Tare Equation

Jet off tares

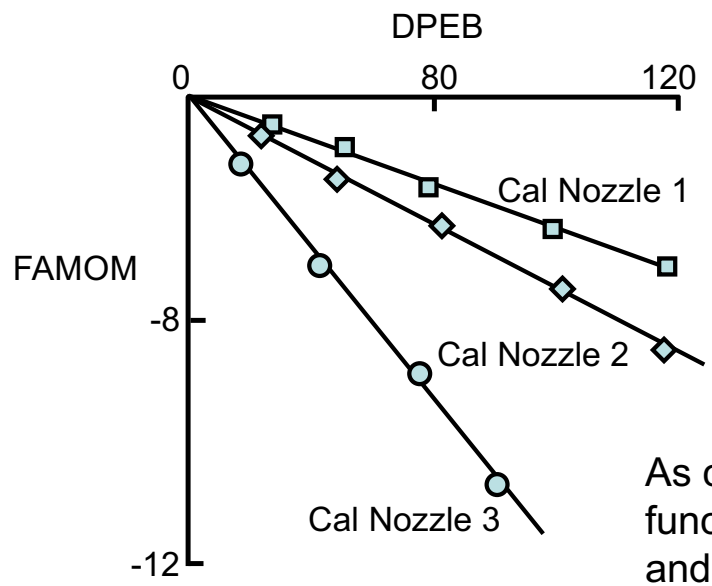
$$TAREN = XK(1,1) + XK(2,1)*FN + XK(3,1)*PM + XK(4,1)*RM + XK(5,1)*YM + XK(6,1)*SF + DELP\ \{(XK(46,1) + XK(47,1)*FN + XK(48,1)*PM + XK(49,1)*RM + XK(50,1)*YM + XK(51,1)*SF + FNO*XK(52,1) + FNO^2*XK(53,1) + PMO*XK(54,1) + PMO^2*XK(55,1) + AREA*[XK(56,1) + XK(57,1)*FN + XK(58,1)*PM + XK(59,1)*RM + XK(60,1)*YM + XK(61,1)*SF] + AREA^2\ [XK(62,1) + XK(63,1)*FN + XK(64,1)*PM + XK(65,1)*RM + XK(66,1)*YM + XK(67,1)*SF]\}$$

Blowing tares

DELP – Bellows Pressure minus free-stream static pressure
FNO – Normal force preload
PMO – Pitching moment preload
AREA – Nozzle area

AXIAL MOMENTUM TARES

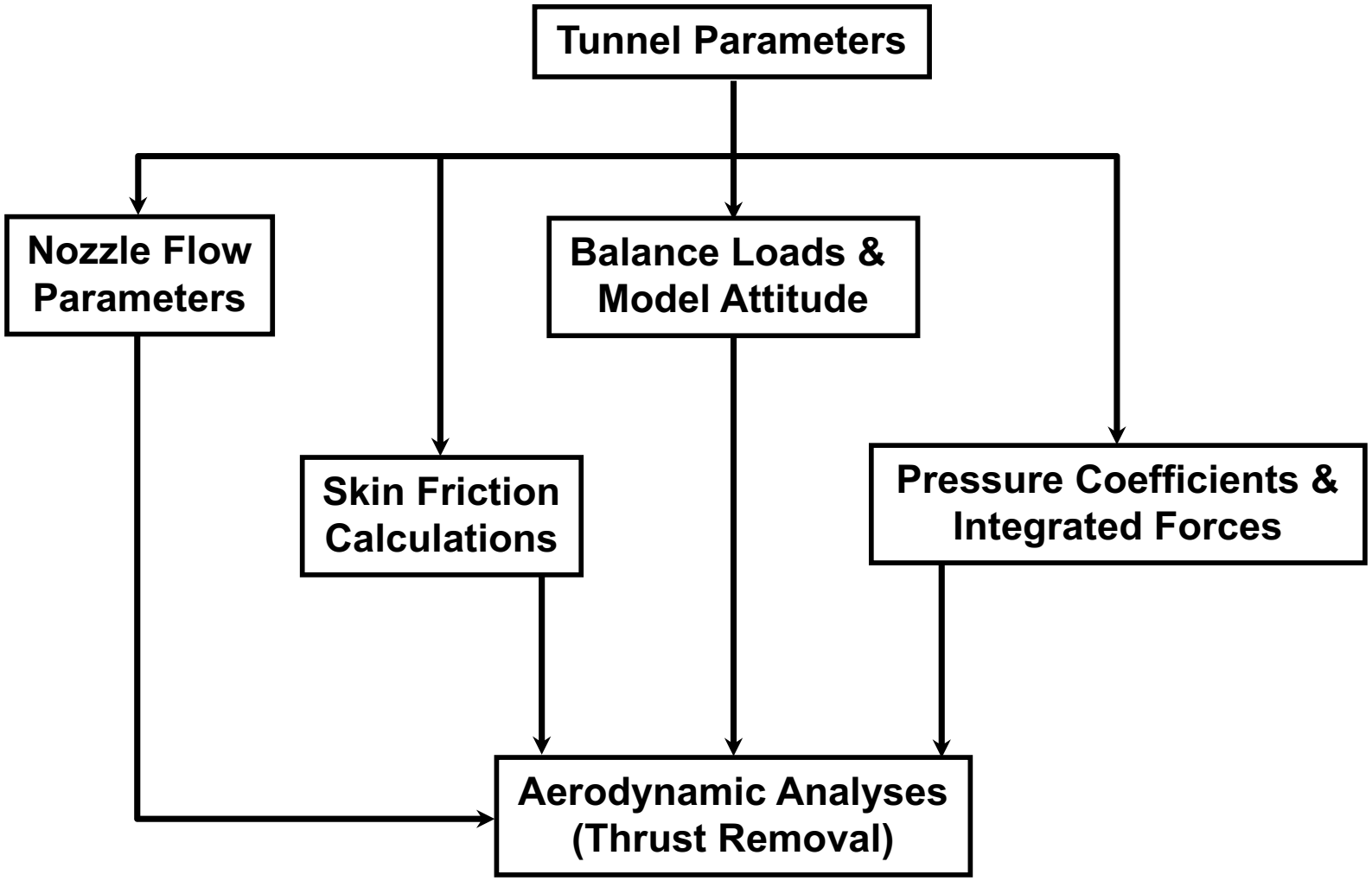
- Determined from the zero-load calibration runs
- All high restraint and all nonblowing corrections applied to data
- Mass flow <u>must be</u> correct, i.e., nozzle discharge coefficient is correct
- Determined by: FAMOM = AF(1,3) - (FJCON/FI)*FI
- FJCON/FI is found by table look-up from historical data on Stratford choke nozzles. Any convergent nozzle could be used as a calibration nozzle as long as its performance is known.



As can be seen, FAMOM is a function of both bellows pressure and nozzle throat area

OTHER DATA REDUCTION REQUIREMENTS FOR PROPULSION TESTING

INTEGRATED DATA REDUCTION PROGRAM



Reference: NASA TM-107646

NOZZLE FLOW PARAMETERS

Nozzle Exhaust Conditions

- Measurement of average total pressure and temperature usually made at a charging station located upstream of nozzle exit

Nozzle Pressure Ratio

- Ratio of average jet total pressure to free-stream static pressure
- NPR = $p_{t,j} / p_\infty$

Nozzle Mass Flow

- Total mass flow w_p obtained from venturi measurements
- Ideal mass flow $w_i = f(p_{t,j}, T_{t,j})$

$$w_i = \frac{p_{t,j}}{\sqrt{T_{t,j}}} A_t \sqrt{\frac{g\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

- Discharge coefficient = w_p / w_i

Nozzle Ideal Thrust

- Ideal Thrust = $w_i = f(\text{NPR}, T_{t,j}, w_p)$

$$F_i = w_p \left\{ \frac{RT_{t,j}}{g^2}\left(\frac{2\gamma}{\gamma-1}\right)\left[1-\left(\frac{1}{\text{NPR}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right]\right\}^{\left(\frac{1}{2}\right)}$$

- Nozzle performance parameter, F/F_i

Reference: NASA TM-107646

PRESSURE COEFFICIENTS & INTEGRATED FORCES

- Eight groups of pressure coefficients could be computed in this module with a maximum of 125 measurements per group
- Calculated quantities from each group consisted of:
  - $C_p = (p - p_\infty)/q_\infty$
  - $C_{F,p} = \sum(C_{p,l})A_l / A_{ref}$
  - $C_{N,p} = \sum(C_{p,l})A_l / A_{ref}$
  - $C_{m,p} = \sum(C_{p,l})A_l / A_{ref}\ c_{ref}$
  - $C_{l,p} = \sum(C_{p,l})A_l / A_{ref}\ c_{ref}$
  - $C_{n,p} = \sum(C_{p,l})A_l / A_{ref}\ c_{ref}$
  - $C_{Y,p} = \sum(C_{p,l})A_l / A_{ref}$
  - $C_{hm} = \sum(C_{p,l})A_l / A_{ref}\ c_{ref}$
  - $C_{D,p} = C_{F,p}\cos\alpha + C_{N,p}\sin\alpha$
  - $C_{L,p} = C_{N,p}\cos\alpha\ \ C_{F,p}\sin\alpha$

AERODYNAMIC ANALYSES TECHNIQUES

(THRUST REMOVAL)

Several options were available to remove thrust and to obtain the various aerodynamic and aeropropulsive parameters required for data analyses. These options worked for both fully and partially metric models. Computed inputs from the previously shown modules were required.

- <u>Some Simplified Thrust Removal Equations</u>
  - Computed jet axial force -- $C_{FJC} = p_\infty/q_\infty\ [k(NPR) + I]$
  - Thrust removed axial force coefficient -- $C_{A,aero} = C_A - C_{FJC}$
  - Computed jet normal force -- $C_{NJC} = p_\infty/q_\infty\ [k(NPR) + I]$
  - Thrust removed normal force coefficient -- $C_{N,aero} = C_N - C_{NJC}$
  - Thrust vector angle -- $\delta_j = C_{NJC} / C_{FJC}$
  - Constants k and i are determined from static runs
  - Similar calculations can be made for the forces and moments

Reference: NASA TM-107646